STRUCTURE AND PETROCHEMISTRY OF THE HAFNARFJALL-SKARÐSHEIÐI CENTRAL VOLCANO AND THE SURROUNDING BASALT SUCCESSION, W-ICELAND

HJALTI FRANZSON B.Sc.

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"Akrafjall og Skarðsheiði
eins og fjólubláir draumar"

S.Þór.

ABSTRACT

This research involves a study of a 2 km thick volcanic succession which accumulated during the opening stages of the precursor of the Reykjanes-Langjökull axial rift zone in W-Iceland, between 6-3 m.y.

Following the initial accumulation of olivine tholeiite lavas, which lie unconformably on an older crustal basement 10-13 m.y.), a central volcano developed in the Hafnarfjall-Skarðs-heiði area. It was active for some 1.5 m.y. and consists of four volcanic phases: I. The Brekkufjall phase is characterized by basaltic volcanism followed by voluminous and copious extrusions of differentiated rocks culminating in a sudden caldera collapse (c.5 km wide) in Brekkufjall. II. During the Hafnarfjall phase a thick extrusive sequence of basaltic to rhyolitic compositions accumulated, mainly fed by ENE fissures. During the gradual subsidence of the Hafnarfjall caldera (7 by 5 km) a marked decrease occurred in lava accumulation rate outside the caldera. Epicentres of three cone sheet swarms coincide in time and space with three basinal structures of this caldera. III. The Skarðsheiði phase is characterized by N-S fissuring and a marked bimodal basalt-rhyolite lava accumulation. IV. Remnants of the Heiðarhorn phase include compositions ranging from basalts to rhyolites. The western boundary of the axial rift zone is marked by large intrusives, basalt flexuring, a sheet swarm and the disappearance of dyke swarms. The lenticular unit was later buried by lavas of the Hvalfjörður lenticular unit.

Rocks of the central volcano follow the Þingmúli trend, but

is discontinuous in the basaltic andesite range. Basalts (frequently porphyritic) with relatively monotonous compositions and low LIL abundancies predominate during episodes of low extrusion rate whereas high elemental dispersion characterizes basalts of high extrusion rate episodes.

The basalt compositions are believed to be controlled more by partial melting processes rather than by episodes of low-pressure fractionation. The differentiated rocks are considered to have predominantly formed by partial melting of the lower crust.

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GEOLOGICAL MAP in a pocket at the back of the thesis.

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CHAPTER 1

INTRODUCTION

1.1 Location and field-work

The Hafnarfjall-Skarðsheiði area lies 30-50 km north of Reykjavík and about an equal distance west of the Reykjanes-Langjökull volcanic zone (fig.1.1). The research area (fig.1.2) measures about 15x45 km extending over approximately 430 km^2. The topography centres on the 700-1000 m high east-west mountain ridge of Hafnarfjall and Skarðsheiði, bounded by the glacially peneplaned lowlands, of Andakíll district to the north and Leirársveit and Melasveit districts to the south. The southern part of the research area includes the Akranes mountain (fig.1.3).

The field-work was done in three stages. Work on the Akranes peninsula was mainly accomplished in one month during the summer of 1970. About 3 months of field-work in the Brekkufjall and the andesitic area to the northeast was carried out in the summer of 1971 as a part of a project for the degree of B.Sc. in geology at St.Andrews University. The remaining and largest part of the research area was mapped during about six months in the summers of 1974 and 1975. Geomagnetic directions of lavas were measured with a portable fluxgate magnetometer. Metamorphic overprinting of the remanent magnetization in the rock posed some uncertainty, especially within the core of the central volcano. However, the problem was frequently resolved by repeated measurements within the same rock formation (fig.1.5).

Endings in Icelandic location names do in some instances indicate the type of locality. These are the most common; -fjall=mountain, -dalur=valley, -á=river, -vatn=lake,-fjörður=firth, -jökull=glacier, -nes=peninsula.

Fig.1.1

A simplified geological map of Iceland.
Data compiled from: Þórarinsson et al.,1973; Pálmason and Sæmundsson, 1974; Jóhannesson, 1975.

Fig.1.2

The approximate areal extent of the research area.

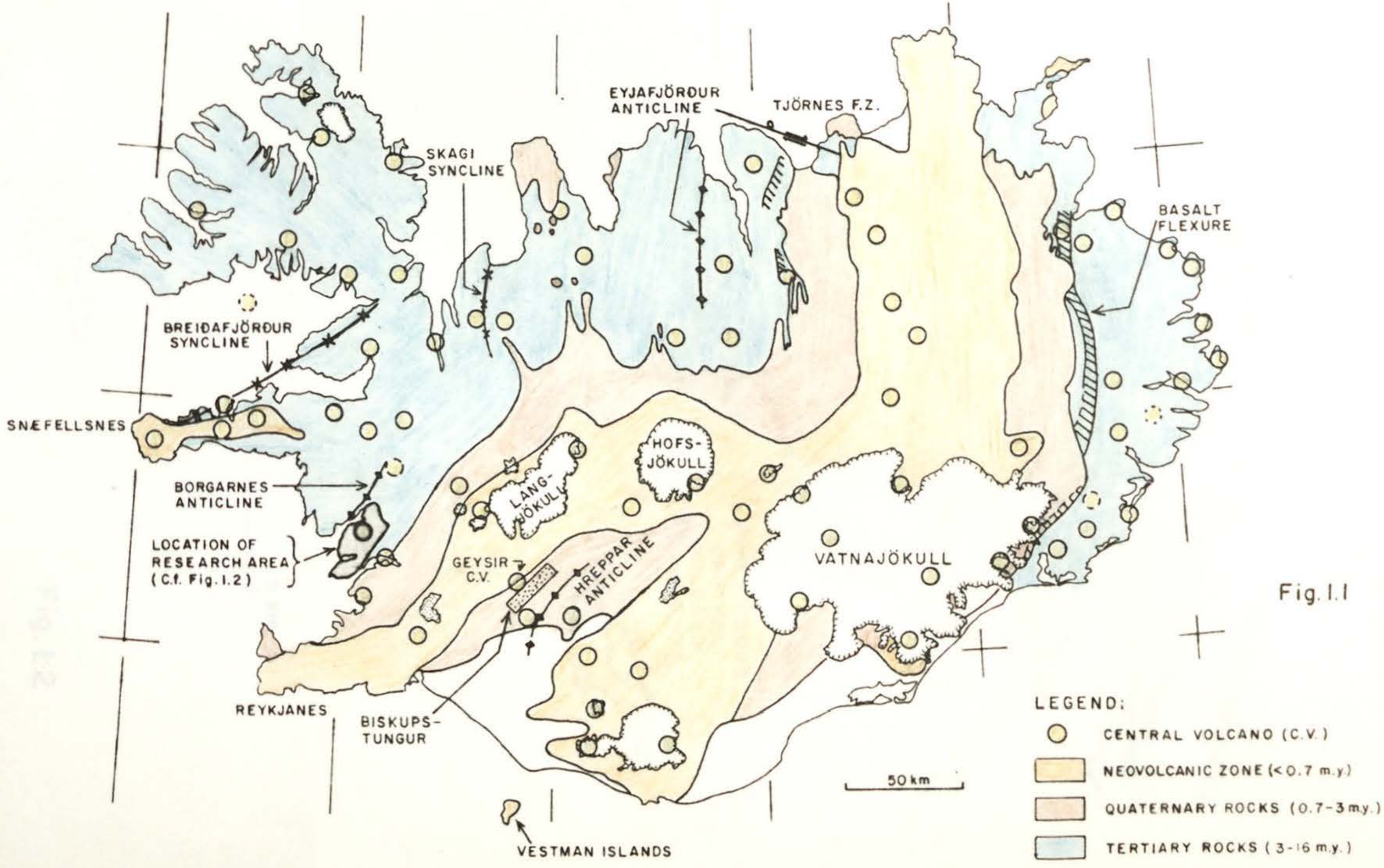
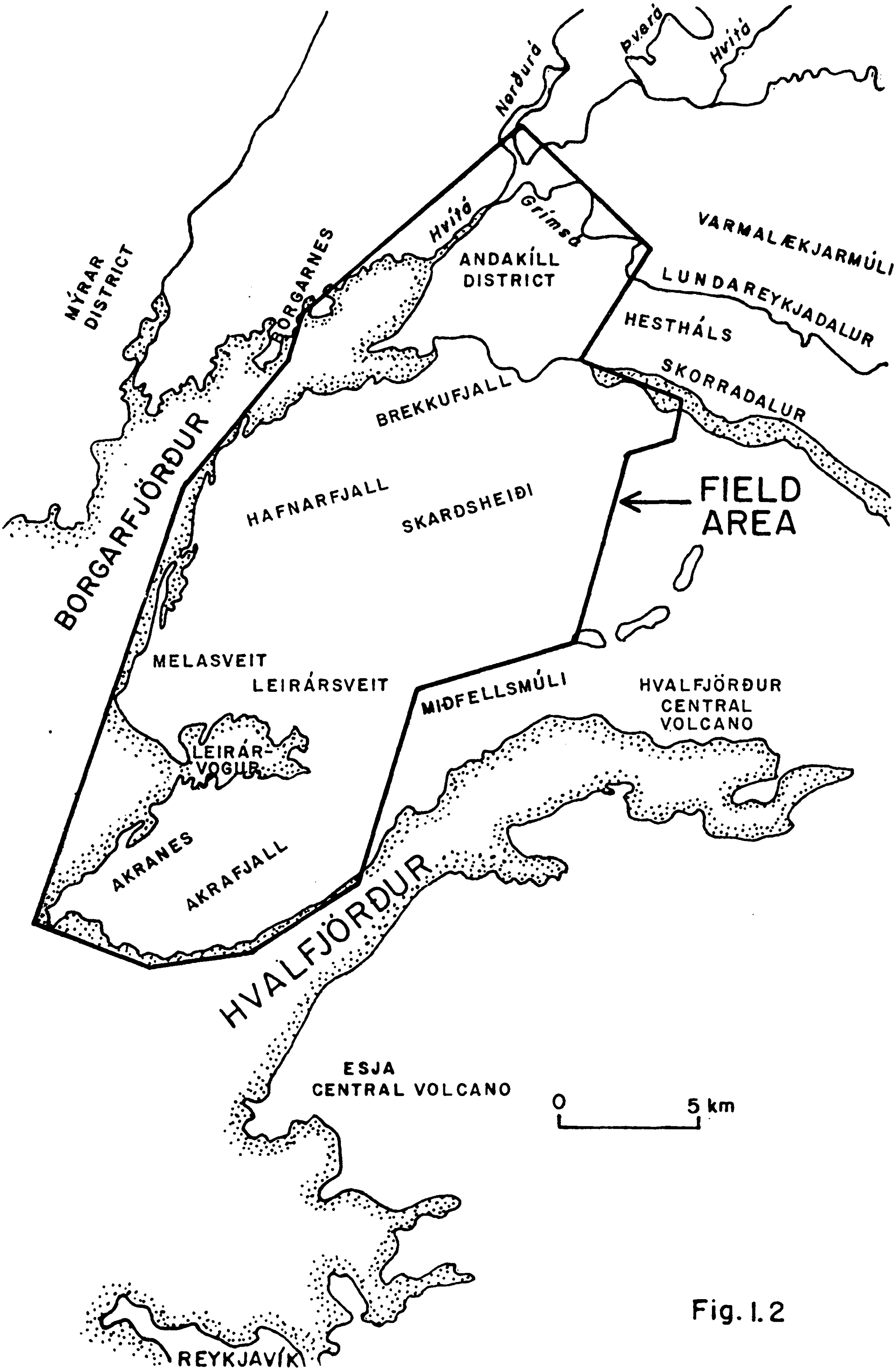

EYJAFJÖRÐUR
ANTICLINE
TJÖRNES F.Z.
SKAGI
SYNCLINE
BASALT
FLEXURE
BREIÐAFJÖRÐUR
SYNCLINE
SNÆFELLSNES
BORGARNES
ANTICLINE
LOCATION OF
RESEARCH AREA
(C.f. Fig. I.2)
HOFS-
JÖKULL
LANG-
JÖKULL
GEYSIR
C.V.
HREPPAR
ANTICLINE
VATNAJÖKULL
REYKJANES
BISKUPS-
TUNGUR
VESTMAN ISLANDS
50 km
LEGEND:
CENTRAL VOLCANO (C.V.)
NEOVOLCANIC ZONE (<0.7 m.y.)
QUATERNARY ROCKS (0.7-3 m.y.)
TERTIARY ROCKS (3-16 m.y.)

Fig. I.I



Norðurá
Þverá
Hvítá
Hvítá
Grímsá
MÝRAR DISTRICT
BORGARNES
ANDAKÍLL DISTRICT
VARMALÆKJARMÚLI
LUNDAREYKJADALUR
HESTHÁLS
SKORRADALUR
BREKKUFJALL
BORGARFJÖRÐUR
HAFNARFJALL
SKARÐSHEIÐI
FIELD AREA
MELASVEIT
LEIRÁRSVEIT
MIÐFELLSMÚLI
HVALFJÖRÐUR CENTRAL VOLCANO
LEIRÁR-VOGUR
AKRANES
AKRAFJALL
HVALFJÖRÐUR
ESJA CENTRAL VOLCANO
0
5 km
REYKJAVÍK

Fig. 1.2

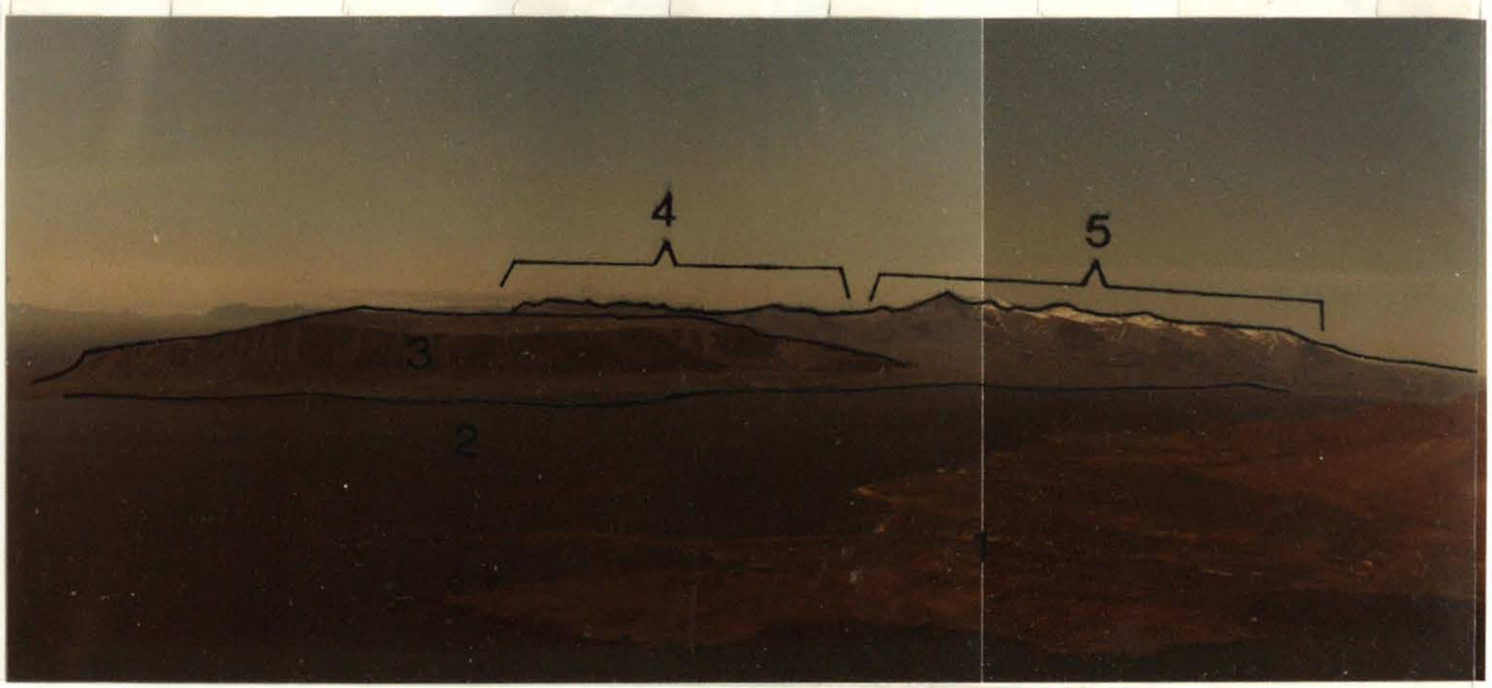


Fig.1.3 A view of the research area towards north

1. The base of Esja central volcano (c.f. Friðleifsson, 1973)

2. Hvalfjörður 3. Akrafjall 4. Hafnarfjall 5. Skarðsheiði.

The representative stratigraphic profiles, along with the magnetic polarities of the lava, are placed near the appropriate text. The approximate locations of the profiles are shown on the geological map, and are also listed in Table A1 in the appendix.

In the field the extrusive rocks were divided into three main categories, viz. rhyolite, andesite and basalt. The basalt was further subdivided into three types, according to the widely used classification of Walker (1963), with the exception that the term olivine tholeiite is used in place of olivine basalt.

Of the three types; tholeiite, olivine tholeiite and (plagioclase-phyric) porphyritic basalt, the principal field distinctions between the first two mentioned are as follows:

Tholeiite	Olivine tholeiite
Very fine grained.	Much coarser in grain.
Weathered crust grey to pale brown. Spheroidal weathering uncommon.	Weathered crust brown to black. Spheroidal weathering common.
Amygdales empty or bearing celadonite, chalcedony, quartz and chlorophaeite, usually without zeolites.	Amygdales bear zeolites. Megascopic, often visible.
Pipe-amygdales and basalt pegmatites rare.	Pipe amygdales and basalt pegmatites common.
Well developed flow structure within the body of flow.	Flow structure confined to a streaking out of amygdales.
Scoriaceous upper lava surface common.	Pahoehoe lava surface structure predominant.

The term compound lava is used where the olivine tholeiite extrusive consist of a number of flow units. These frequently represent a cross section of eroded shield volcanoes of Skjaldbreiður type, and are accordingly named compound lava shields.

The third basalt type is the porphyritic basalt (the phenocrysts of which are predominantly plagioclase with subordinate pyroxene and olivine). This term is used, where the phenocryst content surpasses 10% of the rock.

The geological map was drawn up using a 1:25.000 topographic map with contour lines at 10 or 20 m intervals. Aerial photographs were also extensively used in the field.

The aim of the thesis is threefold:

Firstly, the research area provides a good stratigraphical and geomagnetic record of over 2 km thickness of volcanic succession.

Secondly, the aim was to attempt to find the relationship between the old crest of the Borgarnes regional anticline and the younger eastern flank.

Thirdly, the aim was to study the geochemical characteristics of the central volcano in Hafnarfjall and Skarðsheiði. Thorough sampling was done through the Heiðarhorn basalt succession which overlies and post-dates the central volcano. A few samples from the Biskupstungur district in S-Iceland were analysed for comparison. It was hoped that the geochemical data obtained might give a good basis for a discussion on the petrogenesis of the volcanic rocks in the area.

1.2 Previous work

The greater part of the information on the area prior to this research is derived form papers dealing with aspects of the regional geology in W-Iceland.

T. Einarsson and Sigurgeirsson (1957) mapped the main magnetic polarity units of the stratigraphic succession in SW-Iceland. Sæmundsson (1967) outlined the structure of SW-Iceland and recognized the relative succession of the five central volcanoes formed within the Reykjanes-Langjökull axial rift zone. He regarded the Hafnarfjall-Skarðsheiði central volcano as being the second oldest in that region succeeding Baula (Reykjadalur (Jóhannesson, 1975)) central volcano in age. He also recognized two major outbursts of acid volcanics, within the Hafnarfjall-Skarðsheiði central volcano, one in Brekkufjall near the base and the second, towards the upper part of the succession, in Skarðsheiði. Pages 2 and 3 of the geological map of Iceland (Kjartansson, 1968, 1960) indicates the research area to be of Tertiary age and also shows within it the distribution of some of the major acid volcanics as well as the two major intrusions, the Hrossatungur gabbro and the Flyðrur granophyre.

Moorbath et al. (1968) dated the oldest rocks on the Borgarnes anticlinal crest and the Flyðrur granophyre by the K/Ar-method as being 13.2$\pm$2 m.y. and 3.9$\pm$0.6 m.y. respectively. A considerably younger age of 9.4$\pm$0.7 m.y. for the Borgarnes anticline crest has been reported by Aronson and Sæmundsson (1975). Piper, (1971) and Gibson and Piper (1972) used the Flyðrur K/Ar-date to narrow the age range of the magnetic units in southwest Iceland, and were able to correlate the volcanic pile with the timescale of geomagnetic reversals (Cox, 1969).

Accordingly, they dated the Hafnarfjall-Skarðsheiði rocks of being of Gilbert age and showed that the latter were subsequently buried during the last reverse event of that epoch.

From the start of this decade "a phase change" has occurred in geological investigation in S- and W-Iceland, from regional reconnisance type of mapping to a detailed systematic stratigraphic mapping. This has mainly been supervised by Kristján Sæmundsson at the National Energy Authority in Iceland. The areas have usually either been mapped as a part of projects for the B.Sc. degree at the University of Iceland or for Ph.D. projects. The greater part of SW-Iceland has at present been mapped in this way. A small overlap in mapping exists in the acid volcanics in the easternmost part of Skarðsheiði, mapped in 1973 by a group of undergraduates from the University of Iceland. Three reports have been written by G.I. Haraldsson (stratigraphy) Kristófersson (dykes) and H. Haraldsson (sediments), but to the authors knowledge, the report on the acid rocks (Sigurðsson) has not yet been submitted.

1.3 Geological setting

Iceland forms the only major sub-aerial part of the Mid-Atlantic Ridge System. The Reykjanes ridge emerges from the sea to form the tip of the Reykjanes peninsula in the southwest of Iceland (fig.1.1). The continuation of the ridge across Iceland is complex and there are two main zones of rifting present. Of these, the western zone runs from Reykjanes NE, to Langjökull where it terminates, whereas the eastern rift zone runs from Tjörnes in the northeast of Iceland to Eyjafjallajökull and reappearing in the Vestman islands in the south. Furthermore, there is a WNW volcanic fracture zone, which runs from Snæfellsjökull to within 30 km of Langjökull (Sigurðsson, 1970).

Recent evidence suggests that the Snæfellsnes F.Z. may be a part of a bigger fracture zone extending further to S-Vatnajökull in the southeast (Sæmundsson, 1974). The northern end of the eastern rift zone is offset by the Tjörnes Fracture Zone, a right-lateral WNW transform-fault zone, which extends to the Kolbeinsey spreading axis, about 100 km northwest of Tjörnes (Sæmundsson, 1974).

Fig. 1.1 shows the distribution of Quaternary and Tertiary rocks in Iceland. The Tertiary regions form a major part of eastern and western Iceland as well as the central northern Iceland and they are characterized by almost wholly subaerial volcanism. The Tertiary-Quaternary boundary is drawn near the base of the Mammoth event in Gauss epoch where the lowest tillite horizon has been found (c.3 m.y.). From that time to the present there are indications of over 20 glaciation periods in Iceland with intermittend icefree interglacials (Friðleifsson, 1975). The structure of Iceland is broadly synclinal about the major axis of rifting, though with two major exceptions (fig.1.1.). In W-Iceland and ENE-WSW trending regional syncline, the Breiðafjörður syncline, runs from the northern shores of Snæfellsnes to Gilsfjörður (Sæmundsson, 1974) and another regional syncline, the Skagi syncline, found in N-Iceland, extends from Húnafjörður (in Húnaflói) in the north, to Arnarvatnsheiði in the south (Sæmundsson, 1974). Bordering these synclines and the rift zones are the Borgarnes and Eyjafjörður regional anticlines. The third anticline in Iceland is the Hreppar anticline, which lies approximately midway between the western and eastern volcanic rift zones in S-Iceland.

Crustal dilation within the axial rift zones occurs predominantly along distinct fissure swarms, arranged "en echelon" with respect to the rift zone (Sæmundsson, 1974). The fissure swarms correlate with dyke swarms in the deeply eroded Tertiary regions. Gibson (1966) observed a lenticular shaped lava structure associated with each dyke swarm, where the thickness of lava succession in each area was roughly proportional to the percentage dyke dilation. The term, lenticular lava unit, is adopted in this thesis.

A central volcano frequently occurs within the lenticular lava units, coinciding with the area of maximum intrusive and extrusive activity. The following features characterize most central volcanoes of the axial rift zones:

a) A life-time of about 0.5-1.0 m.y. (Piper, 1971; Sæmundsson 1972).

b) Rocks of acid and intermediate compositions are nearly exclusively confined to the central volcanoes. A bimodal distribution, with maxima at the basic and the rhyolitic ends and a minimum in the intermediate composition range, is generally observed.

c) Caldera subsidences are common with diameters of 5-15 km. Cone-sheet swarms are often closely related to the calderas.

d) Most major intrusions in Iceland occur in the core regions of deeply disected central volcanoes. The high intrusion rate is a likely cause for the high temperature gradient and the extensive hydrothermal aureole found in the core of central volcanoes.

e) A characteristic feature of many central volcanoes is that the flanks are composed of thin basalt flows, where each flow usually measures less than 4 m.

Opinions differ on how appropriate the name, central volcano, is, as in many cases distinct boundaries between the basalt volcanism of the central volcano and the basalts of the surrounding lenticular unit are rarely encountered, but are most often gradational over long distances. Furthermore, repeated eruptions from a centrally situated vent as the name implies, is not a common feature in the presently active central volcanoes of the axial rift zone. The view adopted by the author, confirmed by the field relations in the research area, is, that the central volcano is an integral part of the lenticular lava unit, as its growth is fundamentally controlled by the same variables, associated with the ascent of magma along a fissure as a result of rifting. The name, however, is retained here, mainly because it already is inextricably established in Icelandic geological literature. Unless

Fig.1.4

The main evolutionary episodes of the research area.

Fig.1.5

Magnetostratigraphic map of the research area.
The geomagnetic time scale is compiled from Cox (1969) and Talwani et al. (1971).

A1-A3 = Rocks older than c. 10 m.y.

B1-B3 = Rocks of probable Epoch 5 age.

C1-C8 = Rocks of Gilbert age.

D1-D2 = Rocks of lower Gauss age.

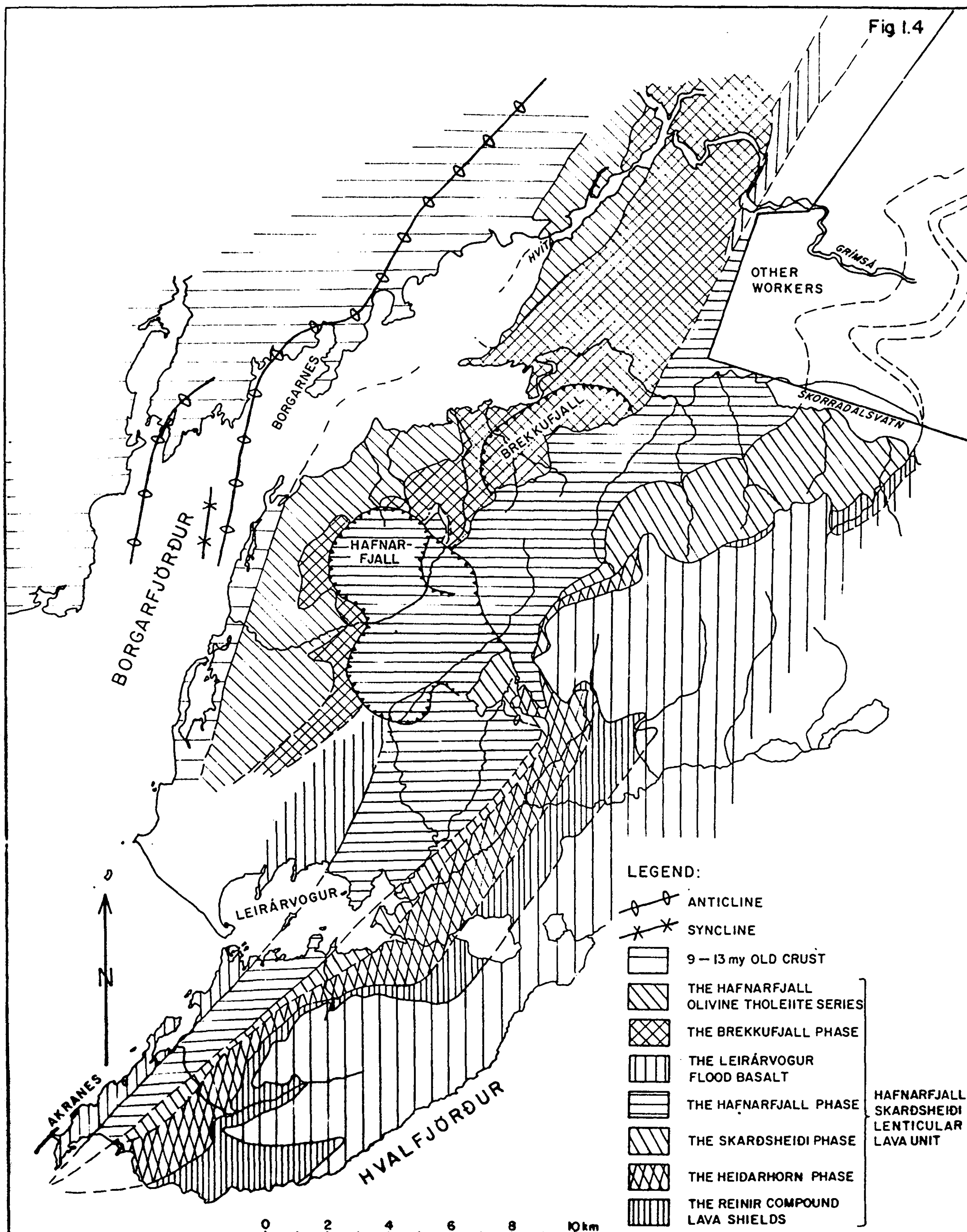
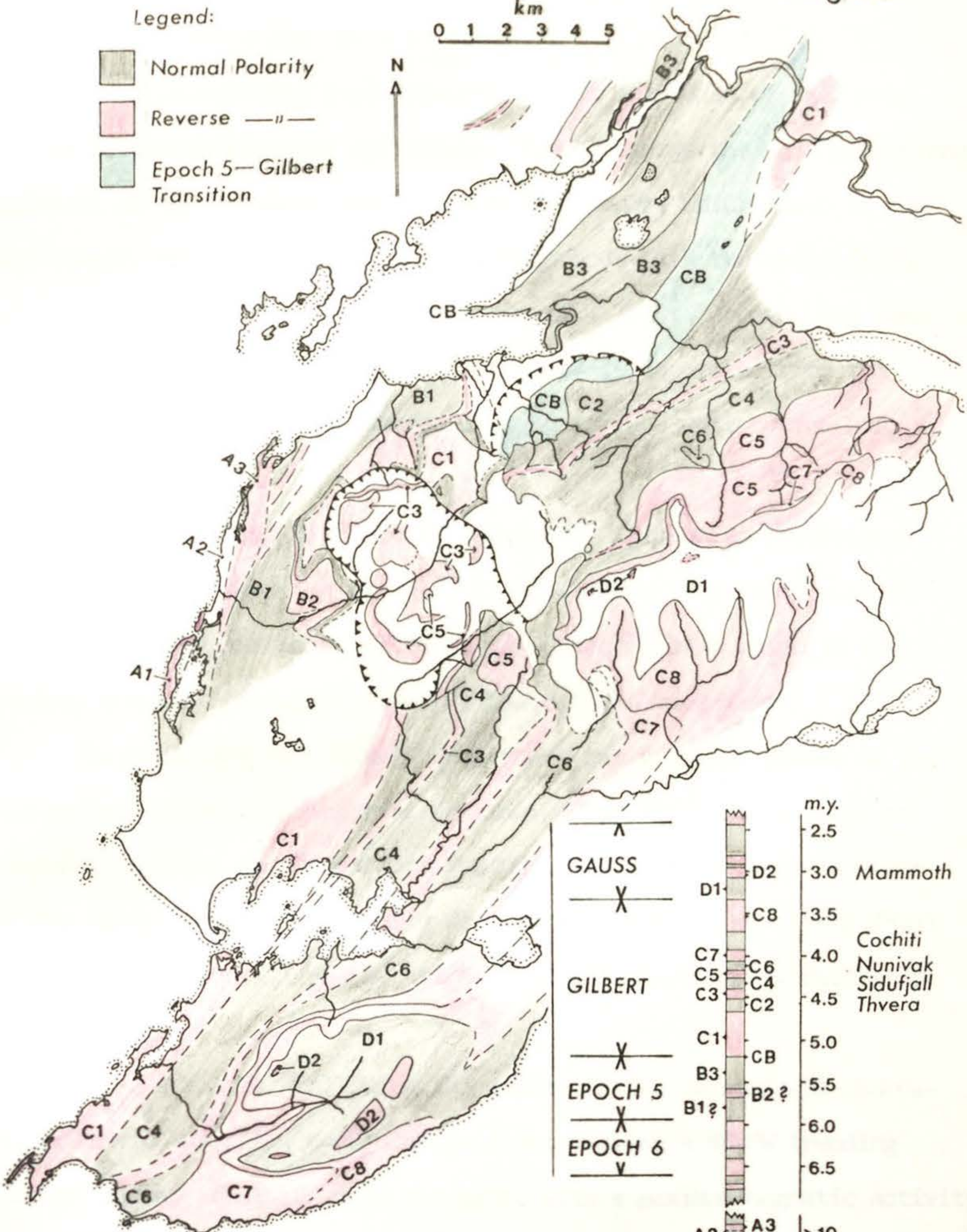


Fig 1.4
OTHER WORKERS
GRÍMSÁ
SKORRADALSVATN
HVÍTÁ
BORGARNES
BREKKUFJALL
BORGARFJÖRÐUR
HAFNAR-FJALL
LEIRÁRVOGUR
N
AKRANES
HVALFJÖRÐUR
0 2 4 6 8 10 km
LEGEND:
ANTICLINE
SYNCLINE
9 — 13 my OLD CRUST
THE HAFNARFJALL OLIVINE THOLEIITE SERIES
THE BREKKUFJALL PHASE
THE LEIRÁRVOGUR FLOOD BASALT
THE HAFNARFJALL PHASE
THE SKARÐSHEIÐI PHASE
THE HEIDARHORN PHASE
THE REINIR COMPOUND LAVA SHIELDS
HAFNARFJALL SKARÐSHEIÐI LENTICULAR LAVA UNIT
HVALFJÖRÐUR LENTICULAR LAVA UNIT

MAGNETOSTRATIGRAPHIC MAP

Fig.1.5



otherwise stated, the areal extent of the Hafnarfjall-Skarðsheiði central volcano is arbitarily defined by the outer perimeter of the occurrances of differentiated rock. Outside this perimeter the term "flood basalt volcanism" will be used.

The research area lies adjacent to and southeast of the crest of the Borgarnes regional anticline. Fig.1.4 shows the main evolutionary episodes of the research area. The oldest rocks, which occur to the north-west, are believed to be contemporaneous with the anticlinical crest, dated at 9-13 m.y. (Moorbath et al., 1968; Aronson and Sæmundsson, 1975). This relatively old "basement" is separated from the overlying Hafnarfjall-Skarðsheiði lenticular lava unit by the Höfn unconformity.

The Hafnarfjall-Skarðsheiði lenticular lava unit, accumulated approximately between 6-4 m.y. is divisible into five major sub-units:

1. Olivine tholeiite flood basalts, accumulated prior to the central volcanic activity, form the base of the succession.

The remaining four sub-units represent the volcanic phases of the Hafnarfjall-Skarðsheiði central volcano. They are distinguished on temporal, spatial and structural grounds, and bear the location name of the focus, where the activity was most pronounced. 2. Brekkufjall phase, 3. Hafnarfjall phase, 4. Skarðsheiði phase and 5. Heiðarhorn phase.

After a hiatus, following the demise of the Hafnarfjall-Skarðsheiði lenticular unit, accumulation started along a NE-SW trending fissure swarm, about 10 km to the west, with a maximum magmatic activity occurring in the Hvalfjörður central volcano. The present investigation was, however, only confined to the lower flood basalt sequences of this lenticular lava unit towards west and southwest.

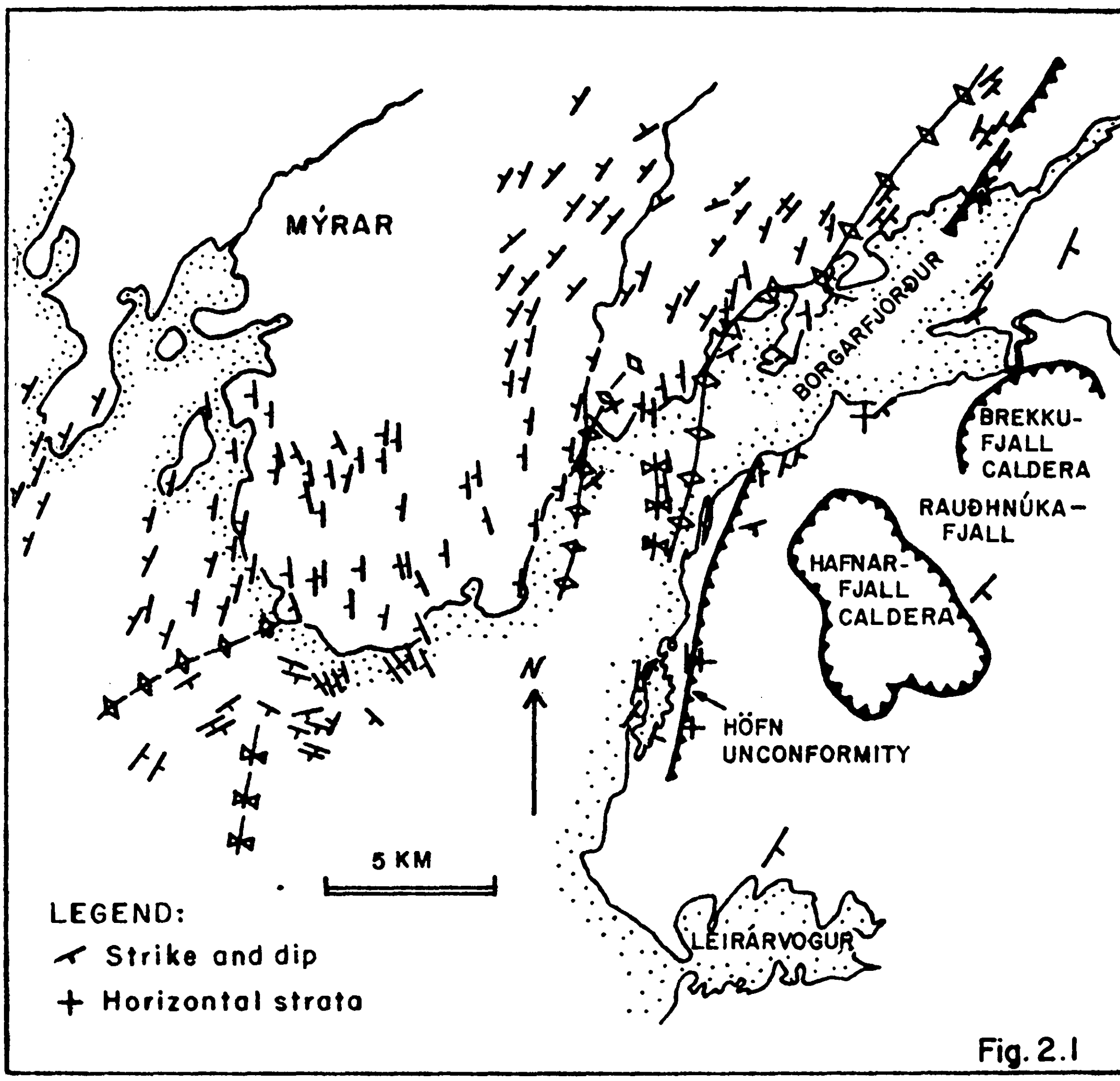
CHAPTER 2

THE FLOOD BASALT SUCCESSION BELOW THE HÖFN UNCONFORMITY.

2.1 The Borgarnes anticline

The crest of the Borgarnes anticline runs from Borgarnes village in the southwest to Hreðavatn in the northeast (Sæmundsson, 1967). The west flank dips towards the northwest to the Breiðafjörður syncline and the east flank dips southeast towards the Reykjanes-Langjökull rift zone (fig.1.1). For most of its length the anticlinal crest is characterized by a single gentle curvature except at its southern end where anomalous dip and strike directions occur. The southern part of the crest is shown in fig.2.1 which is plotted from aerial photographs. These anomalies comprise on a macroscale, a lateral 60° rotational change in strike direction, from the regular NE-SW strike direction observed to the north. The strike directions are apparently concentric about a centre situated approximately in Rauðhnúkafjall (between the two calderas). This is further complicated by two small anticlinal and synclinal structures with their axes plunging south. The structural anomaly within the basalt succession terminates about 10 km west of Borgarfjörður, west of which the basalt pile attains its normal NE-SW strike direction.

The K/Ar-dates of 13.2 $\pm$ 2 m.y. (Moorbath et al., 1968) and 9.4 $\pm$ 0.7 m.y. (Aronson and Sæmundsson, 1975) of the anticlinal crest at Borgarnes are anomalously high with respect to the ages obtained from the geomagnetic mapping in the research area to the east of the crest, which gave a nearly continuous record from the Mammoth event in the Gauss epoch (about 2.9-3.0 m.y.) to the lower half of Epoch 5 (about 5.5-6 m.y.). This age discrepancy, can however be explained by the angular unconformity,



Strikes and dips of the southern part of the Borgarnes regional anticline.

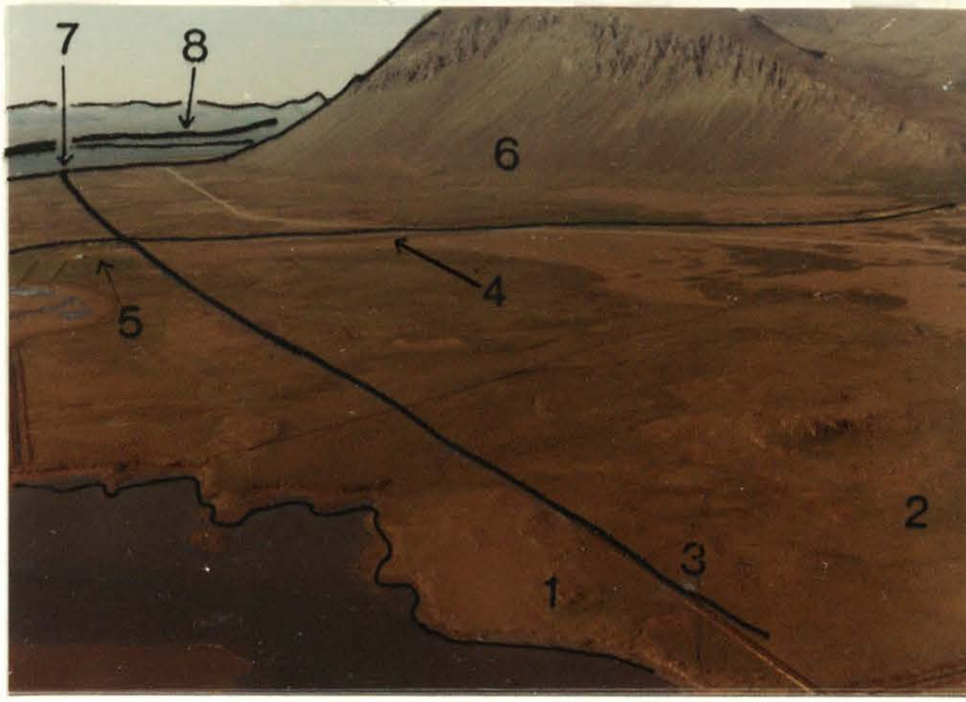


Fig.2.2

A view of the lowlands west of Hafnarfjall towards north.

1. Lavas dipping 15-20°E 2. Horizontal lavas
3. Approximate alignment of the Höfn unconformity
4. The Hafnará 5. Höfn farm 6. Western Hafnarfjall
7. Borgarfjörður 8. Borgarnes regional anticline

the Höfn unconformity (fig.2.2), present on the lowlands west of Hafnarfjall (see the geological map). It is best seen in the Hafnará just northeast of Höfn farm, where thick, tilted, porphyritic lava flows underlie horizontal tholeiite lava flows. The unconformity can be followed southwards for about 5 km where it disappears beneath a sedimentary cover of the last glaciation. Exposures are scarce north of Hafnará, but the unconformity probably runs north out into Borgarfjörður east of Straumeyri. The unconformity is likely to be present east of Hvítá underlying the porphyritic basalt sequence west of Ferjubakki farm. The unconformity is likely to represent a hiatus in volcanic activity lasting 3-7 m.y. A major unconformity has been reported at a similar stratigraphic level by Jóhannesson (1975), about 30 km north of the research area. These field relations conform well with a recent attempt to explain the formation of regional anticlines in Iceland (Aronson and Sæmundsson, 1975). The basis of this explanation is that during the last 10 m.y. the ridge axis shifted repeatedly eastwards due to a relative westward drift of the oceanic crust over a stationary hot-spot beneath Iceland (Sæmundsson, 1974). The location of an extinct ridge axis can be recognized by a regional synclinal structure. Aronson and Sæmundsson postulated that the anticlinal structures (especially the Borgarnes and the Eyjafjörður anticlines (see fig.1.1)) formed essentially as a result of shifting of spreading axis whereby each flank of the anticline originated from a different spreading regime. Accordingly, the oldest exposed part of the Borgarnes anticline below the unconformity may have originated from within the Breiðafjörður spreading axis which became extinct 6-7 m.y. (Moorbath et al., 1968). The eastern flank, above the unconformity, is then derived from the Reykjanes-Langjökull volcanic rift zone.

The effects of this crustal boundary upon the structural and tectonic evolution of the Hafnarfjall-Skarðsheiði central volcano is discussed in chapter 6.

2.2 The basalt succession

a. The Belgholtsnes Olivine Tholeiite Series

The poor exposures of the series, which is located in Belgholtsnes, southwest of the Höfn farm, does not allow the construction of a reliable stratigraphic column. Its thickness is at least 160 m (possible faults not taken into consideration), and may be considerably greater as its base lies offshore. Although the outcrops do not allow precise measurements of individual lava thicknesses, the average thickness probably lies in the range of 4-6 m. The series has a dip of 16-20° east and the strike direction gradually changes from NE-SW in the south to N-S at the northern tip of the peninsula. The lava flows are reversely magnetized.

b. The Hafnarskógur Porphyritic Series

This series overlies the Belgholtsnes Olivine Tholeiite Series and is found within a zone approximately 1 km wide running from Narfastaðaós in the south to Straumeyri in the north where it disappears into Borgarfjörður. The total thickness is likely to amount to about 300 m disregarding the possibility of faulting. The top of the series is defined by the Höfn unconformity. As in the underlying series, the strike direction trends approximately NNE-SSW in the Narfastaðaós area, but changes to a N-S direction north of Hafnará. The dip of the basalts also show some variation, but usually from 13-16°. At two locations, however, both near the unconformity, the inclination exceeds 20°. While exposures are scanty the majority of the flows are plagioclasephyric with pyroxene phenocrysts present in subordinate amount. On the east shore of Narfastaðaós, however, two 5 and 10 m thick olivine tholeiite flows occur, separated by two 5 m thick tholeiite flows. At least three tholeiite flows are seen in this dominantly porphyritic succession to the north at two different levels. The predominance of the porphyritic basalts may be exaggerated to a certain extent by their greater erosional resistance and relatively abundant outcrop compared to the intervening tholeiites and olivine tholeiites. While the majority of the porphyritic lava flows are believed to lie in the 7-15 m range, about 1.5 km north of Höfn farm, two densely porphyritic lavas attain thicknesses of at least 20 m; these lavas were mistakenly identified as gabbro intrusions on the regional geological map. Intercalated sediments were not found, mainly due to the lack of exposures at the boundaries of lava flows. On geomagnetic criteria the series is divided into two groups. The lower 200 m is normally magnetized whereas the upper 100 m are reversely magnetized with the exception of a normally polarised tholeiite flow south of Straumeyri. On the Einarsnes peninsula on the north side of Borgarfjörður, a group of porphyritic basalt lavas overlies olivine tholeiite lavas. One of the flows is remarkable for the large size (up to 2 cm) of its plagioclase phenocrysts. Both the porphyritic and olivine tholeiite lavas show normal polarity and the whole series may possibly correlate with the lower part of the series west of Hafnarfjall. The northeast-ward continuation from Einarsnes was not found, and it is to be assumed, that the group is either blanketed by younger lava formations or obscured in a densely faulted area northeast of Bóndhóll farm.

CHAPTER 3

THE HAFNARFJALL-SKARÐSHEIÐI LENTICULAR LAVA UNIT

3.1. Introduction

The initiation of the lenticular unit is marked by the accumulation of the Hafnarfjall Olivine Tholeiite Series above the plane of the Höfn unconformity. The remainder of the overlying succession is contemporaneous with the Hafnarfjall-Skarðsheiði central volcano (c.f. fig.1.4). Four distinct eruptive phases are recognizable in the central volcano, each of which produced rocks ranging from basalts to rhyolites. Commencement of each phase involved a shift in the area of the maximum rate of lava extrusion.

1) The Brekkufjall phase produced extrusives that are largely confined to the lowlands of the Andakíll district. The westward continuation of this "Brekkufjall sub-unit" is restricted by the western rim of a graben, which is believed to have developed shortly before the commencement of the central volcanic activity. The lowest part of the Brekkufjall sub-unit comprises mainly tholeiite flows with a few intercalations of basaltic andesites. This is overlain by a thick formation, mostly of andesites, representing a very voluminous discharge produced during a brief eruptive episode culminating by a caldera collapse. The Brekkufjall phase closed with the accumulation of the Tungukollur Tholeiite Series which solely outcrops to the west of the graben.

During a brief hiatus following the demise of the Brekkufjall phase, flood basalt volcanism dominated giving rise to the Leirár-vogur Porphyritic and Compound Series.

2) The Hafnarfjall phase gave rise to a sub-unit consisting

of thin tholeiite basalt flows in Hafnarfjall and above Brekkufjall. Two rhyolite domes were also formed, one near the base of the succession in Rauðhnúkafjall, and a younger one in Rauðihnúkur, at the west corner of Skarðsheiði. A caldera formed during about the middle of this phase in the area of highest basalt extrusive rate, some 4 km SW of Brekkufjall caldera. The caldera was filled with eruptives of basalt and andesite lavas and hyaloclastites.

3) The Skarðsheiði phase; activity recommenced in the Skarðsheiði region some 6 km ENE of the Hafnarfjall caldera. A pronounced bimodal distribution of rock compositions in this phase involves; a) tholeiite basalt (thin flows wedging out west against the Hafnarfjall succession and b) rhyolite (domes, lavas and between Skessuhorn and Drageyraröxl, in northern Skarðsheiði, ignimbrites). Andesitic rocks are poorly represented.

4) The Heiðarhorn phase can be less certainly identified. This yielded a 100 m (+) sequence of thin tholeiite basalt and scarce andesite lavas at the western margin of Skarðsheiði.

The demise of the lenticular lava unit is marked by the partial burial of the central volcano by the Reinir Compound Lava Shields.

3.2 The succession below the central volcano

a. The Hafnarfjall Olivine Tholeiite Series

The series crops out on the lowlands west and north of Hafnarfjall and along the lower slopes of Ölver, Hafnarfjall and Tungukollur. Further north it extends from Kistuhöfði to about 4 km northeast of Ferjubakki farm. The series lies unconformably on the Hafnarskógur Porphyritic Series and is also locally separated from the overlying Hvanneyri Tholeiite Series of the Brekkufjall phase by an unconformity.

The strata are horizontal or shallow dipping towards the east or southeast. Notable deviations occur however, and can be attributed to two main types of disturbances:

a) Concentric updoming around the following three major intrusions, which were emplaced at the north and west side of Hafnarfjall, during the first and second central volcanic phases; (i) the Tungukollur granophyre, (ii) the Flyðrur granophyre and (iii) an inferred intrusion south of Flyðrur (chapter 5).

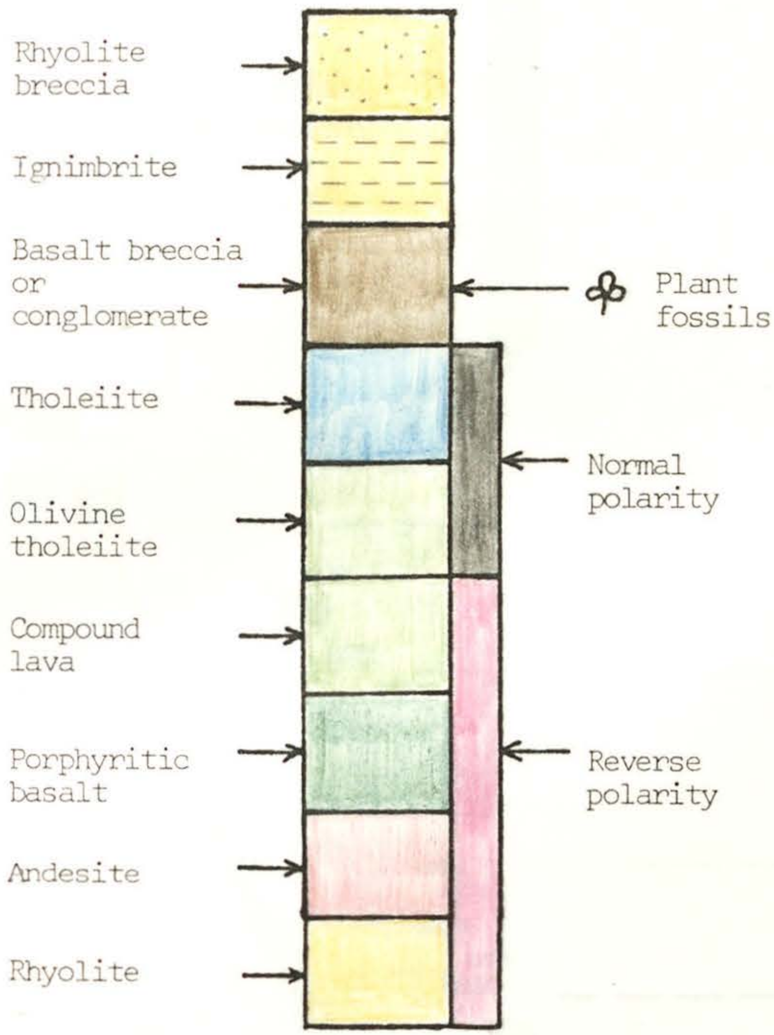
b) Steepening towards the Ölver-Hvítá and the Skálafjall-Grjóteyri flexures (chapter 6).

Although the overall thickness of the series is difficult to assess, there appears to be a pronounced thickening towards the northeast from about 200 m in Ölver area to 300-400 m in the northern Hafnarfjall area. The profiles in fig.3.1 demonstrate this northward thickening and suggest, that the lava series originated in the north, and gradually spread further south discordantly overrunning the older flood basalts. While the series is almost exclusively made up of olivine tholeiite basalts, a few flows of tholeiite and porphyritic basalt occur near its base. The average lava flow thickness appears to be 4-5 m. Sediments also occur but compose a very subordinate part of the series. There are two sediment horizons, each about 2 m thick. The lower horizon lies near the bottom of the series within a tectonically disturbed lavas east of Straumeyri and is composed of lacustrine thinly bedded conglomerates, sandstones and clays. Two 20 cm lignite beds, occurring in the upper part of the horizon, contain well-preserved tree leaves. The upper horizon occurs at an altitude of c. 200 m in eastern Tungukollur and Hafnardalur. It is lithologically similar to the lower horizon but lacks lignites.

Fig.3.1

Stratigraphic profiles of the Hafnarfjall Olivine Tholeiite Series. The location of numbered profiles are shown on the geological map. The legend below applies to all profile figures in text.

LEGEND:



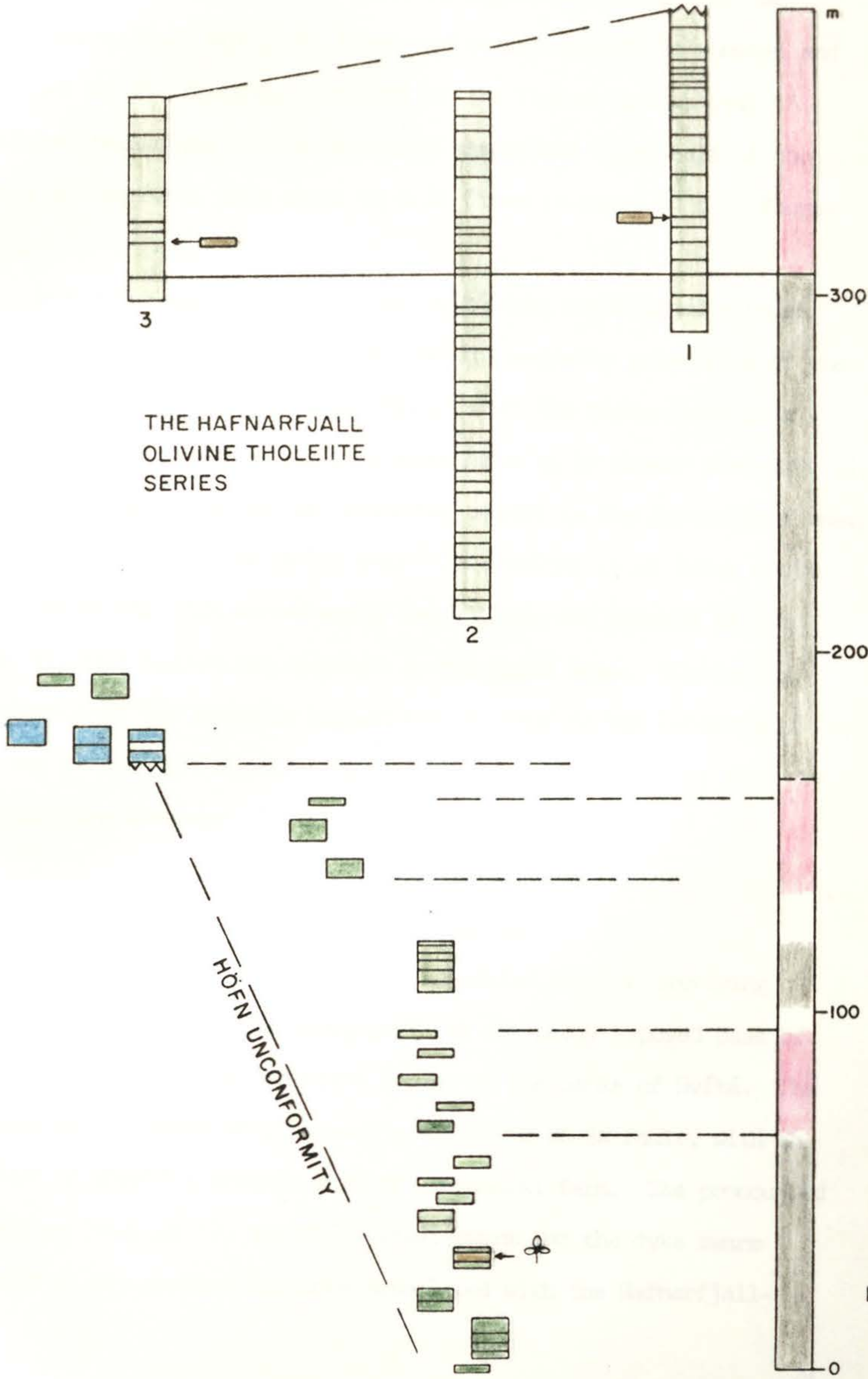

m
300
200
100
0
3
2
1
THE HAFNARFJALL
OLIVINE THOLEIITE
SERIES
HÖFN UNCONFORMITY

Fig.3.1

The geomagnetic record is well established for the upper half of the series but less certain for the lower half. The lower 300 m of the series is likely to be normally magnetized except for two short reversals of which the lower one occurs east of Straumeyri and the upper on the lowlands southwest of the Flyðrur granophyre. A northward thickening of the reversely magnetized upper half of the series is observed, from about 50 m in Ölver to about 80 m in Tungukollur.

Reconnaissance mapping in the Hvítá area established a rough outline of the basalt stratigraphy and the magnetic polarities of the lavas. A likely correlation in fig.3.2 with the Hafnarfjall area, shows the lower olivine tholeiite succession to be absent around Hvítá, whereas a normally magnetized sequence, absent in the Hafnarfjall area, tops the sequence in the Hvítá area. The banking up of lavas against the plane of the Höfn unconformity may explain the absence of the lower normally magnetized sequence in the Hvítá area. Similarily, the absence of the normally magnetized sequence in the Hafnarfjall area may be due to the differing degree of erosion prior to cover by the overlying Hvanneyri Tholeiite Series.

b. The Hvítá differentiated extrusives

One or two intermediate lavas, separated from an overlying rhyolite lava by tholeiite lava, occur at the badly exposed base of the Hafnarfjall Olivine Tholeiite Series at the banks of Hvítá. The rhyolite may be correlated, across a 150-200 m NE-SW fault, with an exposure of rhyolite breccia west of Ferjubakki farm. The pronounced alteration (chapter 7), the Hvítá sheet-swarm and the dyke swarm (chapter 6) are younger features associated with the Hafnarfjall-

Fig.3.2 A rough stratigraphic correlation of the Hafnarfjall Olivine Tholeiite Series between Hvítá and Hafnarfjall areas.

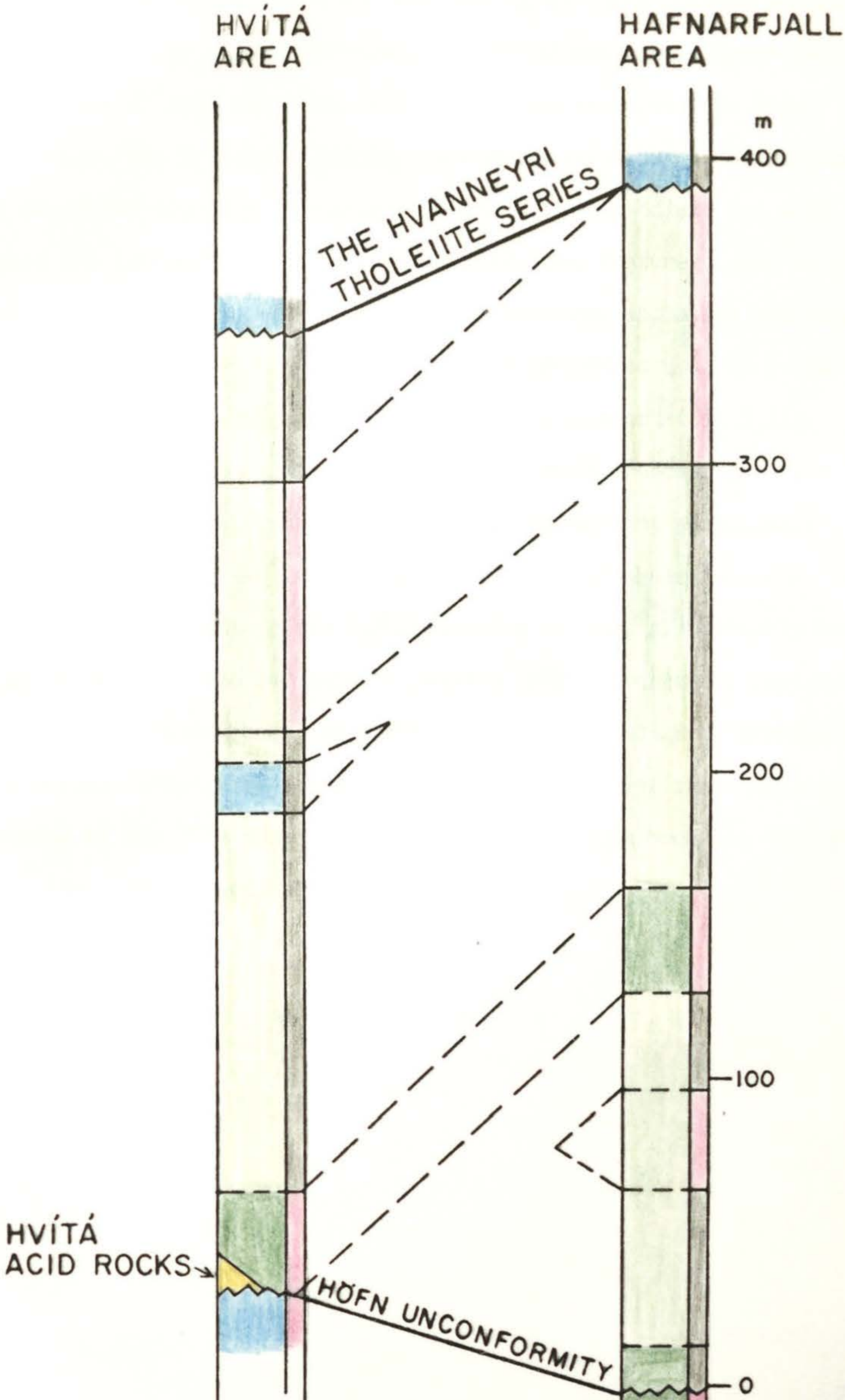

HVÍTÁ
AREA
HAFNARFJALL
AREA
m
400
300
200
100
0
THE HVANNEYRI
THOLEIITE SERIES
HVÍTÁ
ACID ROCKS
HÖFN UNCONFORMITY

Fig. 3.2

Skarðsheiði central volcano, which commenced activity approximately o.3 m.y. later.

Occurrences of differentiated extrusive rocks outside central volcanoes in the axial rift zones of Iceland are rare. Apart from the Hvítá example only two other such localities are presently known:

(i) The Hallarmúli differentiated rocks, about 30 km northeast of the Hvítá locality, includes a number of intermediate and acid lavas and ignimbrite sheets. Central volcanic features, such as a hydrothermal aureole, dyke swarm and geophysical anomalies are absent.

(ii) Sæmundsson and Aronson (1975) described an acid horizon immediately east of the Eyjafjörður anticlinal crest (fig.1.1), consisting of a few sheets of ignimbrite, which are overlain by a sequence of entirely unaltered basalts. (Sæmundsson, pers.comm.).

The tectonic and stratigraphic features of these two areas is very similar to that of the Hvítá locality as they all directly overlie a major break in the Tertiary succession near the crest of regional anticlines. These rocks, according to the postulation of Aronson and Sæmundsson (1975), are among the earliest extrusives from the initial opening of new rift zones, which were at that time breaking through the older lithospheric plate.

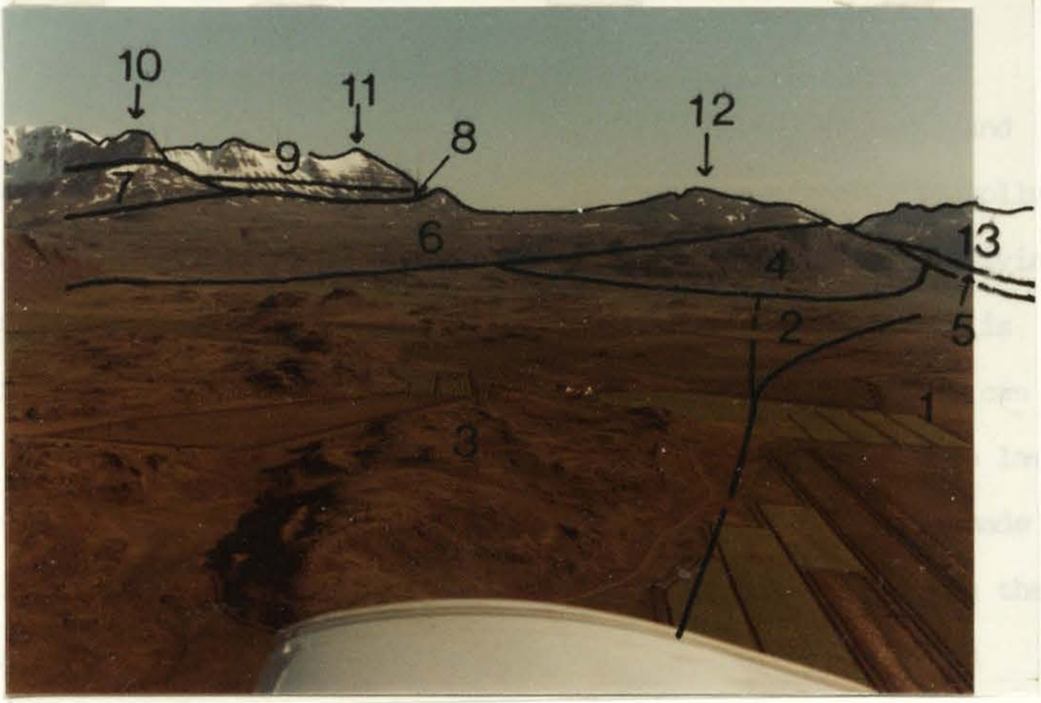


Fig.3.3

A view southwards to Hafnarfjall and Skarðsheiði.
1. Hvanneyri Tholeiite Series 2. The lower sequence of the Flank Series 3. The upper sequence of the Flank Series 4. The Brekkufjall Caldera Series 5. The Skálafjall-Grjóteyri flexure 6. The Hafnarfjall Tholeiite Series 7. The eruptives of the Skarðsheiði phase 8. The basalt succession of the Heiðarhorn phase 9. The Hvalfjörður lenticular lava pile 10. Skessuhorn 11. Heiðarhorn 12. Rauðhnúkafjall 13. Hafnarfjall.

3.3 The Brekkufjall phase

The rock sequence extruded during the Brekkufjall phase has been divided into; a) the Hvanneyri Tholeiite Series and b) an overlying andesitic series that will be referred to as the Brekkufjall Acid Series.

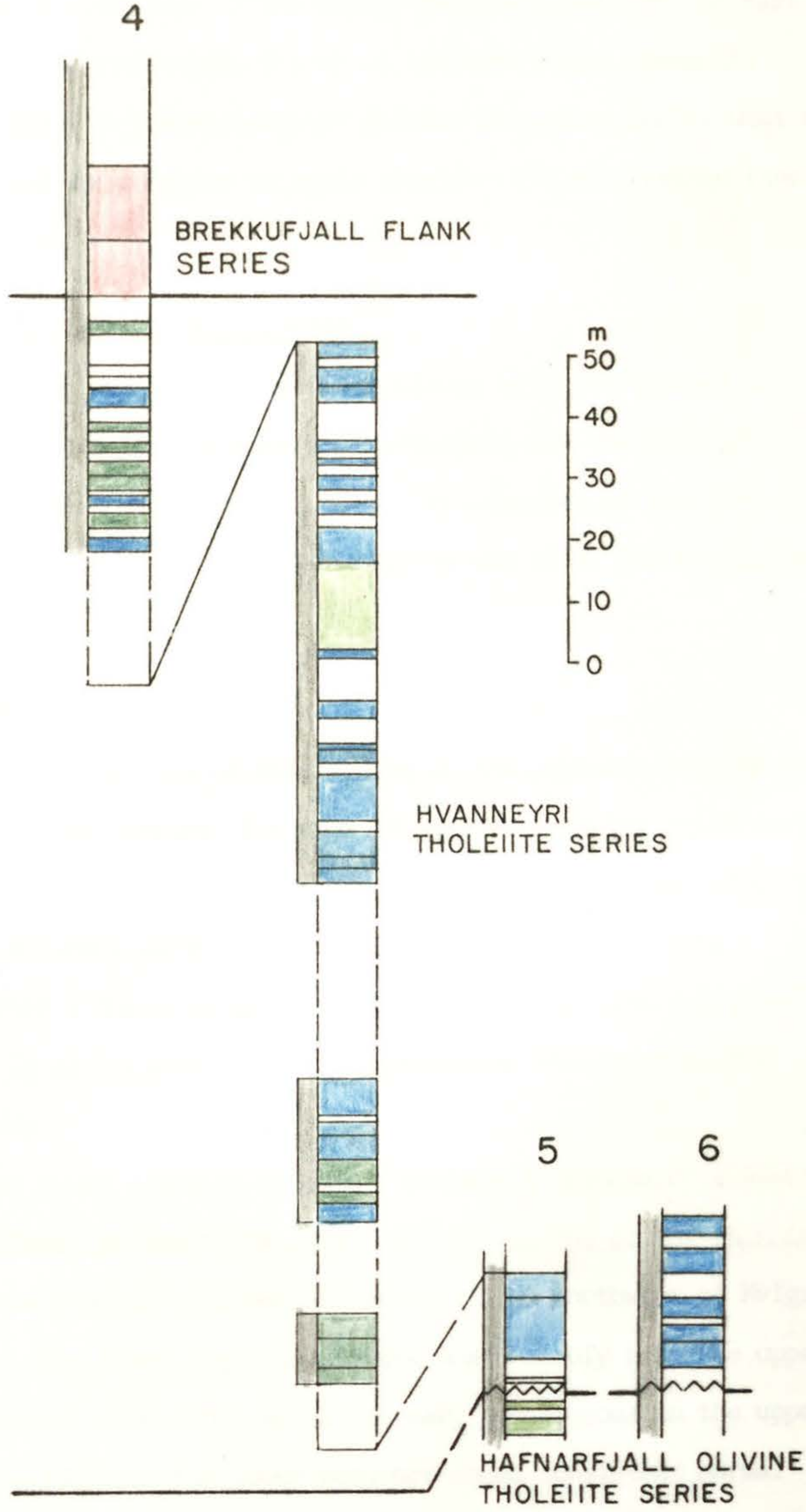
a. The Hvanneyri Tholeiite Series

This series occurs mainly in the Andakíll between Grímsá and Kistuhöfði peninsula and probably extends as far south as Tungukollur and Ölver. It locally rests unconformably on the Hafnarfjall Olivine Tholeiite Series. The upper boundary in the lowlands (fig.3.3) is marked by the onset of the Brekkufjall Flank Series. As far as can be ascertained the series is over 250 m thick and has an average lava thickness of 4-5 m. As shown in fig.3.4 the series is largely made up of tholeiite lavas except for a few porphyritic flows towards the top and bottom of the series. Two thick basaltic andesite flows outcrop south of Hvanneyri farm. Sediments in the sequence are believed to be of insignificant thickness. The lavas in general dip 15-17° SE, but show locally, such as north of Kistuhöfði, deviations from that, which are chiefly attributable to the updoming of the roof above the Hvanneyri intrusions (chapter 5).

The series shows a consistent normal magnetization, this property is the main criterion for tracing the series west across the Skálafjall-Grjóteyri flexure (chapter 6) into the Hafnarfjall region. In Tungukollur the series measures about 60 m thinning southwards to about 45 m in Ölver. A 1-5 m thick rhyolite breccia layer is found towards the top of the sequence at these locations. The lavas are on the average about 7-8 m thick.

The differences in the overall thickness and average flow

Fig. 3.4


4
BREKKUFJALL FLANK
SERIES
m
50
40
30
20
10
0
HVANNEYRI
THOLEIITE SERIES
5
6
HAFNARFJALL OLIVINE
THOLEIITE SERIES

thicknesses of the series across the Skálafjall-Grjóteyri flexure can partially be explained by the higher extrusion rate to the east of the flexure. Furthermore, the older and more rigid basement, believed to underlie the Hafnarfjall Olivine Tholeiite Series west of the flexure, may be a factor in their greater flow thicknesses (see also chapter 6).

b. The Brekkufjall Acid Series

This series comprises a very voluminous suite of extrusives, mostly andesitic, which outcrops in Brekkufjall and the lowlands between Andakílsá and Grímsá (fig.3.3). It consists of two structurally distinct formations; (i) The Flank Series and (ii) The Brekkufjall Caldera Series.

(i) The Flank Series

The scanty outcrops of this series in the lowlands overlie the Hvanneyri Tholeiite Series; the name is derived from its relationship to an inferred eruptive centre in Brekkufjall. It consists of up to 700 m thick sequence of andesite lavas in the south, thinning northwards over a distance of 10 km so that it is absent just north of Grímsá. It is divided into two sequences as indicated on the geological map:

1) The lower sequence reaches a maximum thickness of 300-400 m (approx. 7 flows, strike NE-SW, dip c.17° SE) in the south, thinning rapidly northeastwards to terminate about 1.5 km northwest of Kvígsstaðir farm. The lower sequence differs most notably from the upper in the absence of xenoliths, which are very conspicuous in the upper sequence. In addition the lower sequence shows consistent normal polarity whereas the upper sequence gives erratic magnetic directions

(see fig.1.5).

2) From Andakílsá in the south the upper sequence maintains a thickness of 300-400 m to within 1 km from Grímsá in the north, where it rapidly thins out and disappears. The (residual) inclination of the lavas west of Hestfjall dip outwards from two, near vertically flow-laminated, andesite plugs south of Kvígsstaðir farm. Further north the lavas conform to the regional dip of c.15° to the E or SE. About 1700 m southeast of Vatnshamravatn, a circular plug (c.70 m in diameter) of glassy, vertically flow-laminated and highly xenolithic andesite cuts the andesite lavas of the lower sequence. Scattered about the rock are rhyolitic lenticles up to 10 cm in length, parallel to the flow-lamination and composing less than 1% of the rock. In thin section irregular veins filled with the rhyolitic component are observed to radiate from these lenses. These veins are believed to have formed initially as cracks due to a stress field around the lenticles, as a result of different temperatures of solidfication of the two components, which, at a late stage, became occupied by the still highly fluid rhyolitic liquid.

A multiple NNE-SSW dyke (dip c.55-70°ESE) cuts through the Hvanneyri Tholeiite Series on the Kistuhöfði peninsula. Its true size is uncertain since its contacts are largely beneath the sea. The large number of units in this multiple dyke (usually less than 5 m each) and their general lack of mutual chills indicates a rapid spasmodic magma emplacement. The rock is predominantly composite (rhyolite/andesite) and resembles closely the composite eruptives of the Brekkufjall Caldera Series (see later). The exact relationship between the dyke and the Flank Series is unclear. However, judging by the distance separating the two localities (c. 5 km), it is possible that the extrusives of the former are above the present erosian level.

Further to the xenolithic nature and the erratic magnetic polarities as points of distinction between the two sequences, the flows of the upper sequence are also in general much thinner, in some instances measuring only a few meters. This is highly anomalous, as the lavas of the lower sequence measure tens of meters.

(ii) The Brekkufjall Caldera Series

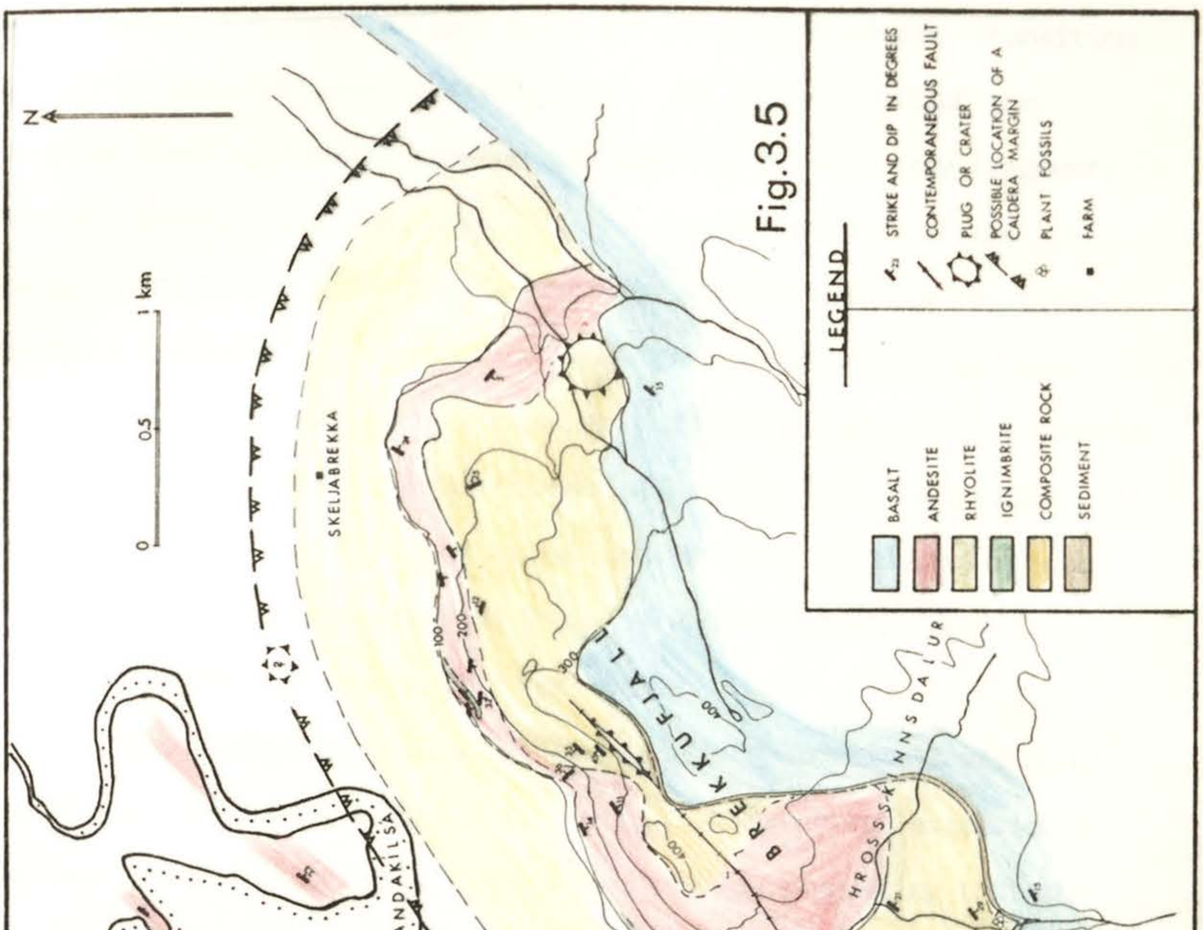
The Brekkufjall Caldera Series (fig.3.5) is the second structurally distinct formation composing the Brekkufjall Acid Series. It consists of a suite of differentiated extrusives (andesites, rhyolites and composite andesite-rhyolite). In the ENE-WSW erosional section, it exhibits a basinal form, reaching a maximum thickness of some 600 m in W-Brekkufjall. The southern part of the series is not exposed, being discordantly overlain by the Hafnarfjall Tholeiite Series (fig.3.3). The Brekkufjall Caldera Series is divisible into six groups, of which 2,3,4 and 5 are erupted within a very short space of time:

1) Lower Rhyolite Group

This group can be traced from Skálafjall in the west to the east margin of Brekkufjall. The larger part of the group is hidden under raised-beach deposits except in Árdalsgil which gives a good crosssection of the group and shows it to consist of three rhyolite flows exceeding 200 m collectively. A progressive southward increase in lava inclination is observed from 21° ESE in the underlying tholeiite flows to over 31° SE in the overlying ash-flow group.

2) Brekkufjall Ash-flow Group

This group, best seen in Árdalsgil (gully), attains a thickness


N
0
0.5
1 km
SKELJABREKKA
BREKKUFJALL
HROSSSKINNSDALUR
ANDAKILSA
ARDALUR
Ardalsgil
SKALAFJALL
GRJOTEYRI
GRJOTEYRI FLEXURE
KISTUHÖFDI
TUNGUDALUR
TUNGUKOLLUR
LEGEND
BASALT
ANDESITE
RHYOLITE
IGNIMBRITE
COMPOSITE ROCK
SEDIMENT
STRIKE AND DIP IN DEGREES
CONTEMPORANEOUS FAULT
PLUG OR CRATER
POSSIBLE LOCATION OF A CALDERA MARGIN
PLANT FOSSILS
FARM
Fig.3.5

of up to 30 m. The basal 3 m is composed of xenolithic rhyolitic pitchstone grading upwards into highly compact and divitrified rock, containing fiammes whose length/breadth ratio approximates to 10/1 (fig.3.8,A). The upper margin shows a 5-10 m thick gradual transition upwards to compact glassy andesite lava. In this transition the andesite first appears as a minor component as black glassy fragments commonly slightly deformed plastically. Towards the top of the transition zone the situation is reversed and the andesite constitutes the major component. The ash-flow component, which now looks quite homogeneous, forms irregular narrow veins filling cracks in the andesite. Two things can be deduced from this relationship; i) The andesite overran the ash-flow while the latter was at least partly molten and ii) there was heat transference from the andesite to the ash-flow, resulting in the latter becoming very fluid.

The 5-6 m ash-flow, found between two thick andesite lavas about 1 km WSW of Skeljabrekka farm, may represent the eastern extension of the same ash-flow. It lacks the pitchstone base suggesting that the underlying andesite remained notably hot.

3) Andesite Group

This group is divisible into two spatially distinct andesite lava sub-groups. The larger occupies the western half of the mountain and exceeds 300 m at its thickest. Within the sub-group, two types of cooling mechanism can be demonstrated. At the outer limits of the sub-group on the southwest side of Brekkufjall, it is made up of 4-6 separate lava flows, each 30-50 m thick. Individual flows are recognized by their division into fine-grained, 4-5 sided columns, overlain by glassy and irregular entablatures, which often appear to be partially fused breccias. The residual dips of the lavas indicate flow towards the north. The cooling history of the interior of the andesite sub-group is excellently revealed on the 250 m northwest face of Brekkufjall (fig.3.6). There, all individual lava structures have been destroyed by the refusion and crystallization of the andesite into a single layer. The layer remains, like the lavas, divisable into two parts. The lower 70-100 m are made up of 4-6 sided columns up to 1 m wide, and the upper part forms the entablature which has a grainsize similar to that of the columns of the individual lava flows.

The second andesite sub-group, which is believed to have erupted approximately simultaneous with the former, occurs in the cliff section southwest of Skeljabrekka farm. It has a maximum thickness of about 150 m and represents the southern part of a cone-shaped formation composed of at least five lavas, dipping 20-35° SE to SW. The (residual) updip directions of the lavas intersect about 600-800 m WNW of Skeljabrekka farm, which locates the most likely position of the conduit (see fig.3.5). As in the earlier andesite sub-group, the lavas accumulated rapidly and represent a single short-lived eruptive event. A collonade-entablature type of lava flow, a possible offshot from the same sub-group, and dipping 5°W runs along the eastern edge of Brekkufjall and disappears under the Hafnarfjall Tholeiite Series.

4) Composite Group

The composite rocks occur in two main areas; a) in Skálafjall where they form the bulk of the mountain, and b) in Brekkufjall, where they overlie the two previously mentioned andesite sub-groups.

The two components of the composite rocks are andesite and rhyolite. The possibility of a minor participation of basalt as the third component cannot be ruled out.

Fig.3.6

The approximately 250 m high cliff section in Brekkufjall exhibiting the refusion of the andesite lavas into one columnate-entablature layer.

The field-relations of flows within the group are imperfectly known. Three factors need to be taken into consideration:

(i) The flow thickness which is, as expected, inversely proportional to the depositional slope. This is well-demonstrated when comparing flow thicknesses at progressive distances from a common vent. The composite rocks in Skálafjall are believed to have flowed from a vent at the west margin of Skálafjall (fig.6.3). In the vicinity of the vent the flows dip steeply west and are usually 1-4 m thick. In Hrossskinnsdalur, about 1.5 km east of the vent, the dip decreases and the average flow thickness increases to about 8 m. A very similar picture is obtained in Brekkufjall when comparing flow thicknesses a) just north of the central feeder and b) on the east margin of Brekkufjall.

(ii) Rate of burial is a second important factor controlling the appearance of a lava flow, as has been demonstrated earlier in the Brekkufjall andesite group. Where the eruptive rate has been high, the scoracious tops and bottoms have been fused into compact rock leaving a joint down to 1 cm in width as the only evidence for the flow boundaries. Such fusion occurs on the cliff SW of Skeljabrekka farm, and also in the lower west side of Hrossskinnsdalur.

(iii) By far the most critical factor determining the physical character of a composite flow is the ratio of the andesite and rhyolite components. The group shows a complete range in this ratio from almost pure andesite flows through to almost pure rhyolite flows. The intimate mixing of the two components is shown in fig.3.8,B. Extrusive and intrusive composite rocks in Iceland have been comprehensively studied by several authors (e.g. Hawkes, 1925; Walker, 1962; Gibson and Walker, 1964; Blake et al., 1965; Walker and Skelhorn, 1966).

Fig.3.8,A

A photomicrograph exhibiting the fiamme structure of the Árdalsgil ignimbrite. The line equals 1 cm.

Fig.3.8,B

A photomicrograph showing the intimate mixing of the andesite-rhyolite components. The line equals 1 cm.

In most of the cases studied, the composites are mixtures of basalts and rhyolites. The evidence is conclusive (e.g. Blake et al., 1965) that, when rhyolite magma is intimately mixed with a hotter basic magma, it becomes heated and its viscosity is markedly lowered. The fluidity is well displayed in Brekkufjall where the majority of the composite flows range in thickness from 1-8 m, contrasting with the 30-60 m thick andesite and rhyolite lavas. Although radical changes in the andesite/rhyolite ratio occur between consecutive flows, significant variation within a vertical section of each individual flow is rare. The interrelationship between the two components are broadly divisible into three categories, depending on the ratio within individual flows.

(a) Rhyolite < andesite

Recognition of the composite nature of such rocks is often difficult because of the slight colour differences between the components. However, the true nature is often revealed by differential weathering. The rhyolite component occurs commonly as flattened lenses, often with a length/width ratios up to 30/1. Such lenses are believed to have provided excellent internal lubricant planes which effectively lowered the viscosity of the whole lava. Flowage of much composite units greatly enhances the mixing of the two components, especially by the rapid elongation along the sliding planes and by injection of the mobile rhyolite component into any fracture in the andesitic part.

(b) Rhyolite > andesite

Here the rhyolite forms the media in which the andesite is incorporated. The andesite, which is clearly chilled against the rhyolite, is seen as angular or wisp-like bodies, with crenulate margins. Again, evidence for the low viscosity of the rhyolite is seen from the manner in which it occupies minute cracks formed in the andesite fragments. Rhyolite flow structure is not observed and this too can be ascribed to its low viscosity.

(c) Rhyolite >> andesite

In this category the andesite component forms less than 10% of the total flow volume. The flow may develop in either of two ways:

a) It may flow as a low viscosity lava. Only one example of this kind has been located (at the northern tip of Skálafjall).

b) The flow may be extruded as an ignimbrite. At least four such flows occur at different stratigraphic levels (5-10 m thick) in the south part of Hrossskinnsdalur, where two of them display good eutaxitic texture. Superheating of the rhyolite component is believed to be the critical factor in the genesis of the ignimbrites of Brekkufjall Caldera Series.

5) Upper Rhyolite Group

This is a typical viscous rhyolite flow, overlying the Composite Group on Skálafjall and supplied from the circular rhyolite plug in central Skálafjall. The maximum lava thickness is about 50 m south of the plug. The unit passes eastwards into rhyolite breccia, which probably is a flow-brecciated lava front. This rhyolite, which also intrudes the composite unit as a 20 m thick sill west of the feeder, represents the last acid extrusive of the Brekkufjall Acid Series.

6) Sediment Group

A sediment layer rests on the Brekkufjall Caldera Series and attains a maximum thickness of about 14 m in Hrossskinnsdalur near the outer margin of the group 5 rhyolite flow. The sediment is composed largely of lacustrine siltstone and contains plant remains. The sediment thins out towards the margins of Brekkufjall Caldera

Series. Above the sediment is a tholeiite flow c. 20 m thick, displaying entablature/collonade structure. The flow is confined to much the same area as the sediment.

The evidence for a caldera structure or a depression containing the Brekkufjall Caldera Series is circumstantial. At the west margin, where the formation banks up against the Skálafjall-Grjóteyri flexure, the talus breccia separating the Caldera Series from the older steeply dipping basalt flows, indicates subsidence immediately preceeding the accumulation of the latter, but it is impossible to make a clear distinction between a subsidence along the N-S flexure and a more curved line as would be expected around a caldera. The Lower Rhyolite Group appears to define about 140° of a circular basin whose outer radius approximates 3 km. The strongest evidence for a caldera structure comes from the presence of the lake sediment above the formation (group 6), along with the thick collonade-entablature lava, which indicates at least 30-40 m elevation difference between the centre and the rim of the depression. Furthermore, the high extrusion rate of groups 2-5 together with the xenolithic nature of the extrusives is consistent with a model involving caldera collapse following rapid emptying of a near surface magma chamber.

(iii) Discussion

Three main lines of evidence suggesting genetic links between the Flank Series (upper sequence) and the Brekkufjall Caldera Series are;

a) The similarity of lava type (andesite) predominating in both areas.

b) The abundance of xenoliths (3 cm or less) in both areas.

The xenoliths show varied lithologies but they are most commonly of basaltic composition. Only two xenoliths of coarse-grained rock (granophyre and gabbro) were found, both in Brekkufjall.

c) Both the upper sequence of the Flank Series and units 2-5 of the Brekkufjall Caldera Series display erratic magnetic directions. Such behaviour is common along boundaries of magnetic reversals. Cox (1969) estimated the time required to complete a polarity transition to be in the order of 10^3- 10^4 years, which demonstrates the rapid accumulation of the differentiated rocks.

The total volume of the differentiated extrusives of the Brekkufjall Acid Series, conservatively estimated to be about 20 km^3, is based on the following assumptions; a) that it is confined to a N-S graben 6-10 km wide. b) It is unlikely to extend further than the southern margin of the inferred caldera (a 2 km borehole at Leirá farm does not intersect such a horizon (Tómasson and Kristmannsdóttir, 1975)). This conforms to the belief that the formation is related in space and time with the Hvanneyri intrusions (chapter 5).

c. The Tungukollur Tholeiite Series

This series, which represents the closing stages of the Brekkufjall phase, is found in the area from Tungukollur, where it banks up against the Brekkufjall Acid Series, to Ölver in the south. The maximum thickness of the series is about 250 m in Tungukollur, where it includes a 60 m thick rhyolite lava towards the top of the series. The number of basalt lavas, as shown in fig.3.9, is just under 40 and they average 4-5 m in thickness. They are mostly tholeiites, except for 8 plagioclase-phyric lavas near the base of the series. The absence of the porphyritic lavas in Ölver may indicate a southward thinning of the series, a similar pattern was noted in the underlying

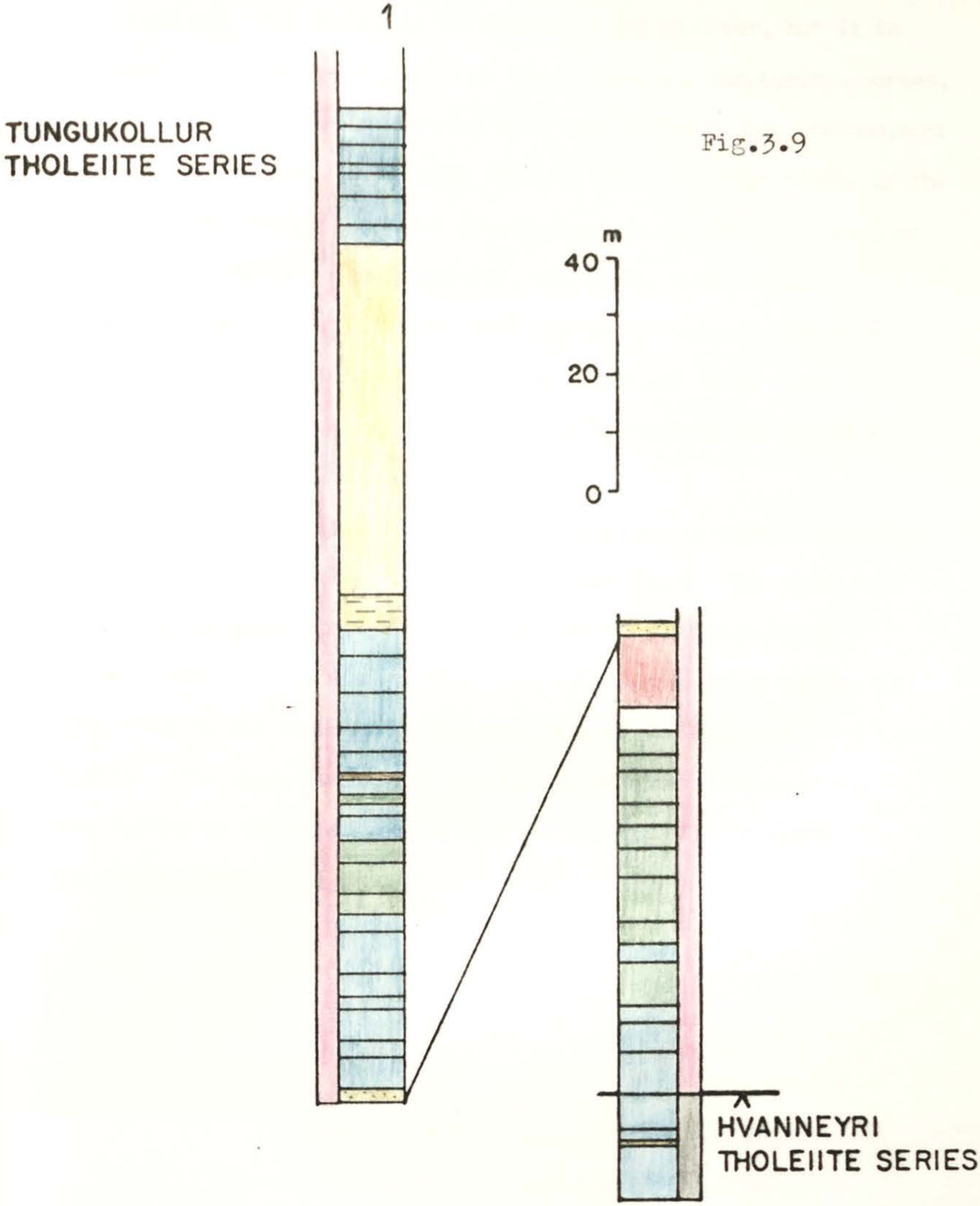

1
TUNGUKOLLUR
THOLEIITE SERIES
m
40
20
0
HVANNEYRI
THOLEIITE SERIES

Fig.3.9

basalt series. The series is not exposed south of Ölver, but it is envisaged either to wedge out below the Leirárvogur Porphyritic Series, or, more likely, to be interbedded with that series. Only one sediment horizon was found, a 2.5. m thick rhyolite tuff, near the middle of the series in Tungukollur. A thick breccia horizon (c. 20 m) occurs just north of the landslide in Tungudalur, containing about equal proportions of angular (< 5 cm) acid and basic fragments and some scattered basaltic boulders up to 2 m in diameter. This layer is thought to occupy the same stratigraphical horizon as the ignimbrite and rhyolite lava in Tungukollur.

A characteristic feature of the series is its reverse polarity, which probably represents the base of Gilbert Epoch. The absence of this polarity group above the area occupied by the Brekkufjall differentiated extrusives suggests that lava accumulation during this time interval was confined to the area west of the Skálafjall-Grjóteyri Flexure. The upper boundary of the series, indicated in southern Tungukollur by the appearance of olivine tholeiite lavas, marks the end of the Brekkufjall phase.

3.4 The Leirárvogur flood basalt succession

a. The Leirárvogur Porphyritic Series

This series outcrops on the north and south shores of Leirárvogur and along the west coast of the Akranes peninsula as far south as the village of Akranes. The series may continue north of Grímsá, overlying the extremities of the Flank Series. The thickness of the series is unknown as its lower boundary is concealed below sea level of the Akranes west coast, but it is likely to exceed 150 m (fig.3.10). The average lava thickness is 6-7 m. Sediments are believed to be negligible. The boundary with the Tungukollur Tholeiite Series is not exposed, but it either interleaves with, or banks up against that series, as previously mentioned. On the Akranes peninsula the lavas dip 14-15° SE, but north of Leirárvogur the inclination increases to 17-19° and the strike becomes more nearly N-S. The change is probably associated with downwarping of the core region of the central volcano. The series is reversely magnetized and is, like the Tungukollur Tholeiite Series, extruded during the lowest reversed interval of Gilbert Epoch.

b. The Leirárvogur Compound Series

The construction of a representative profile of this series proved not possible, mainly due to the limited outcrops and the lack of suitable tracer beds within the series. The series, which overlies the Leirárvogur Porphyritic Series, thickens from Blautós (c.90 m) northwards to Leirárvogur (c.200 m). The thinness of the series (c.30 m) in Tungukollur and its absence above the Brekkufjall Acid Series, may suggest that the extrusives of the Brekkufjall phase were topographically elevated over the surrounding lava fields. A probable thickening to c. 400 m is indicated at the Leirá borehole to the

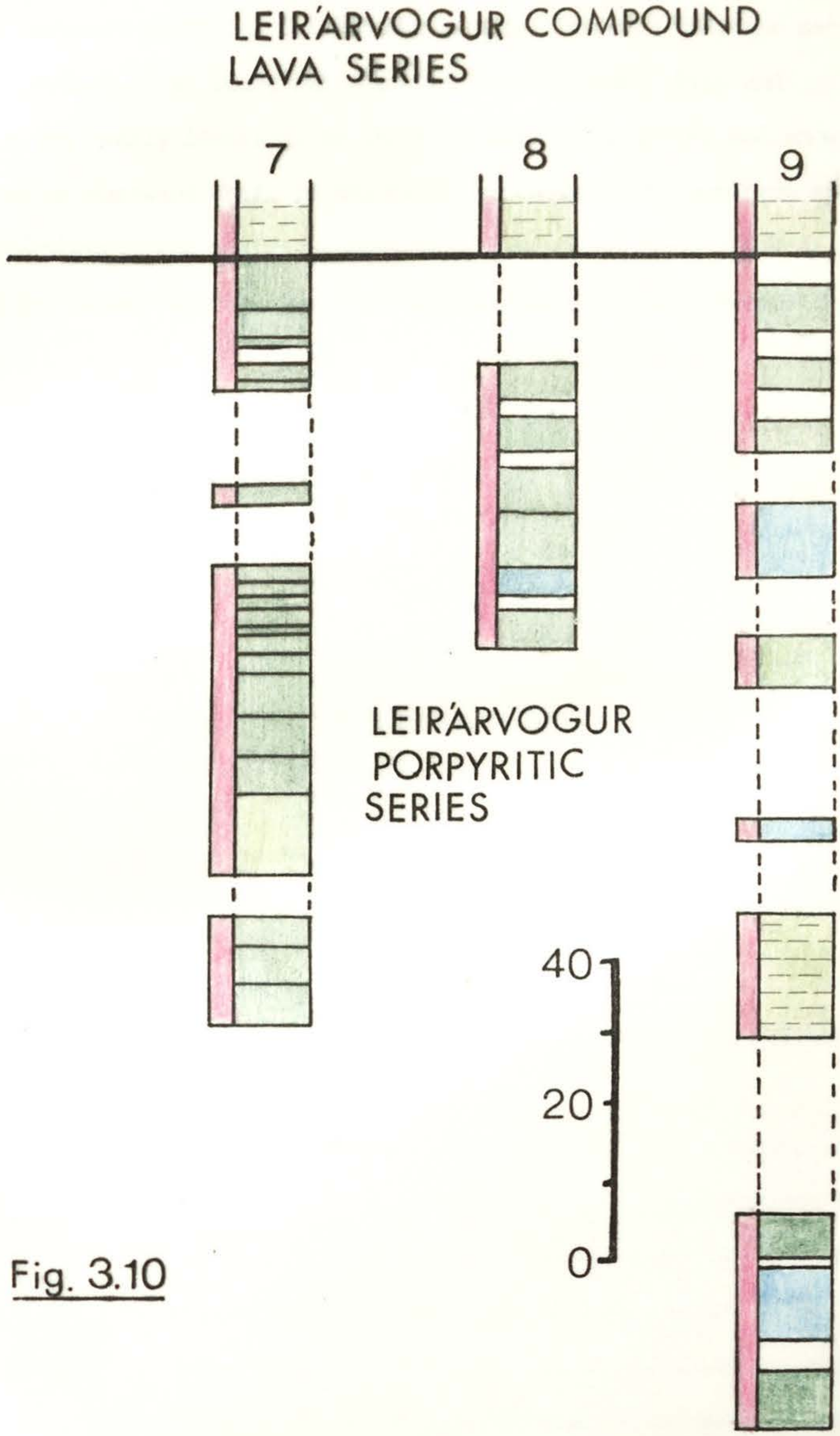

LEIR'ARVOGUR COMPOUND
LAVA SERIES
7
8
9
LEIR'ARVOGUR
PORPYRITIC
SERIES
40
20
0

Fig. 3.10

northeast of Leirárvogur (Tómasson and Kristmannsdóttir, 1975). A tholeiite lava interleaves with the olivine tholeiite compound lavas at the northern shores of Leirárvogur and may indicate that the series is the product of at least two compound lava shields. Dips and strikes are nearly identical to those of underlying series and show the similar eastward shift in dip direction towards the northern side of Leirárvogur. The series is reversely magnetized, and like the underlying Leirárvogur Porphyritic Series, formed in the lower Gilbert Epoch.

3.5. The Hafnarfjall phase

a. The Hafnarfjall Tholeiite Series

The basalt series consitutes the largest part of the Hafnarfjall phase. This is described from two localities: (i) The Central Succession, between Brekkufjall and the sediment horizon cut by the Skessuhorn gabbro and (ii) The Southern Flank Succession. A summary (section (iii) below) is given on the equivalent stratigraphic succession on the north of the field area, derived from the work of geology students from the University of Iceland, and others (e.g. McDougall et al.,1977). Section (iv) below discusses the estimates of the lava extrusion rate and a discussion of the relationship between the flood basalt succession and the central volcano.

(i) The Central Succession

Fig.3.11 gives a representative cross section of the succession between the western end of Skorradalsvatn and the northeastern rim of the Hafnarfjall caldera. The base overlies the Brekkufjall Acid Series (c.f. fig.3.3). The thick sediment horizon into which the Skessuhorn gabbro intrudes delineates the upper boundary of the succession.

The tholeiite succession in this area is over 400 m thick with an average lava thickness around 3.5 m. A 20-30 m olivine tholeiite compound lava unit in the lower part of the succession, seen in Hestfjall and on the east margin of Brekkufjall, wedges out southward and disappears south of Skálafjall. A probable northward continuation is found in the Grímsá gorge, but bad exposures do not allow any thickness comparisons (Smárason, 1975). A thick flow (15-20 m) occurs a few flows above the olivine tholeiite lava unit. From its thickness and flinty fine-grained nature it was tentatively identified as basaltic

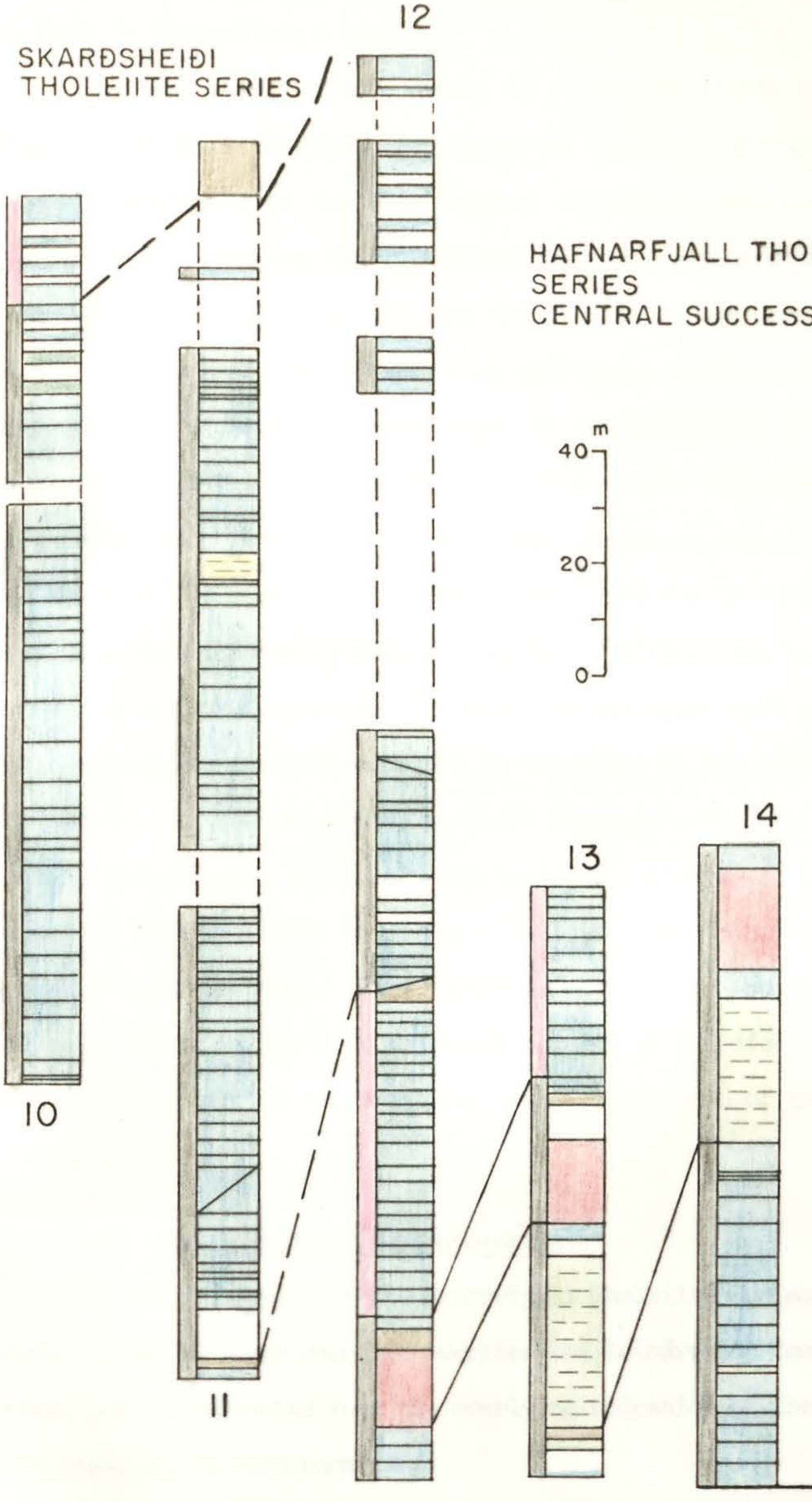

12
SKARÐSHEIÐI
THOLEIITE SERIES
HAFNARFJALL THOLEIITE
SERIES
CENTRAL SUCCESSION
m
40
20
0
14
13
10
11

Fig. 3.11

andesite. This is traceable for about 8 km, from the southern part of Hestfjall to Hrossskinnsdalur.

Only four pyroclastic horizons (> 1 m) occur within the succession of which the lower two appear at the lower and upper margins respectively of the lava sequence displaying reverse magnetic polarity, which separate the Thvera and Sidufjall geomagnetic events of the Gilbert epoch. Both are less than 5 m thick and consist of basaltic conglomerates with tuffaceous matrices. The same horizons are found east of Hestfjall where they are accompanied by pitchstone breccia (10-15 m thick) of probable ash-flow origin (Þóroddsson,1975). The third horizon is a 5 m thick unsorted, pumiceous rhyolitic breccia, only found in the upper part of Hornsdalur. The fourth horizon is about 10 m thick, unsorted angular basaltic tuff-breccia, incorporating sporadic acid rock fragments. It occurs in the upper part of the basalt succession in Hornsdalur and is traceable to the north end of Leirárdalur. It is not present north of Skorradalsvatn, but in Skorradalsháls (Þóroddsson, 1975) and Varmalækjarmúli (Smárason, 1975) a transition from tholeiite to porphyritic lava flows coincides with the same stratigraphic level. This horizon appears to be the only noticeable break in the lava accumulation, and is therefore tentatively put as the boundary to the overlying basalt succession of the Skarðsheiði phase.

(ii) The Southern Flank Succession

The southern part of the Hafnarfjall Tholeiite Series is best exposed in Leirárvogur where it overlies the Leirárvogur Compound Series, and is separated from the overlying volcanics of the Skarðsheiði phase by an unconformity.

The succession measures about 250 m in Leirárvogur (assuming no faulting) with an average lava thickness of under 6 m. Tholeiite lavas predominate, with a few flows of porphyritic basalts. However, porphyritic lavas appear to be of greater importance in the lowlands south of Leirárvogur. This may either be due to the greater erosional resistance of the porphyritic lavas or due to a genuine southward increase in the ratio of porphyritic : non-porphyritic lavas. Sediments appear to be rare, as no sediments thicker than 0.5 m were found.

(iii) Basalts contemporeaneous with the Hafnarfjall Tholeiite Series north of the research area

The following account, which is based on data presented by Smárason (1975), Þóroddsson (1975) and McDougall et al. (1977), describes briefly the basalt succession corresponding to the Hafnarfjall Tholeiite Series north of the research area. This period involved a) the Thvera event (normal polarity) b) a reversed event and c) the Sidufjall event (normal polarity).

The 380 m thick sequence in Hvítársíða (McDougall et al.,1977), about 30 km to the northeast, is notable for the high average lava thickness (c.9 m) and the high proportion of sediments (about 25%). These features show that the sequence is typical for a flood basalt series rather than the product of rapid accumulation from a central volcano.

The stratigraphic equivalent succession in Hestháls and Varmalækjarmúli, bordering the research area, shows characteristics intermediate between these two extremes and exhibits a thickening of flows towards the upper margin of the phase, and a thinning of lavas at the onset of the Skarðsheiði phase, reflecting the diminishing rate of lava accumulation of the former and the vigorous activity at the onset of the latter.

(iv) Discussion

The work of McDougall et al. (1977) included K/Ar-dating through the stratigraphic equivalent of the Hafnarfjall Tholeiite Series north of the research area together with precise geomagnetic measurements for each lava. These allow evaluation of the rate of accumulation for both lavas and sediments. Table 3.12 summarizes their results as deduced from the representative stratigraphic column, in relation to the corresponding basalt succession of the Hafnarfjall phase. As mentioned previously, three geomagnetic events occur within the lava succession of Hafnarfjall phase which accumulated during some 0.5.m.y. The Tvera event lavas show lateral thickness changes due to the topographic relief of the underlying Brekkufjall Acid Series, from 150 m above Brekkufjall to at least 260 m in northern Hestfjall (Þóroddsson, 1975). The sudden drop in the lava extrusion rate (as well as the appearance of sediments) during the overlying reverse event in the Central Succession, relative to the adjoining area to the north (reaches 180 m in Hesthâls), coincides with the Hafnarfjall caldera collapse and its subsequent infilling. Taking into account these features of the succession south and southeast of Brekkufjall, the thickness of basalt accumulated within the lenticular lava unit during the Hafnarfjall phase probably reaches a maximum of 650 m. It is of interest to note that the total lava thickness (280 m) in the flood basalt region to the north is only about half that found in the central volcanic area, whereas the average rate of eruption within the central volcano (assuming one lava equals one eruption) during this half million years is four times that of the flood basalts.

A strikingly different picture emerges on the southern flank, where the lavas erupted during the Hafnarfjall phase wedge out southwards

Table 3.12

The lava extrusion rates within the research area during the Hafnarfjall, Skarðsheiði and Heiðarhorn phases, in comparison with those in the Hvítársíða area (McDougall et al., 1977).

GEOMAGNETIC EVENTS	TIME LIMITS (m.y.)	DURATION (yrs)	NO.OF LAVAS	TOTAL THICKNESS(m)	AVERAGE FLOW THICKNESS(m)	1m/x-yrs	1LAVA/x-yrs
FIELD AREA							
THVERA (C2)	4.81 - 4.60	210,000	38	260	7	810	5,500
REVERSE (C3)	4.60 - 4.45	150,000	19	45	2	3,300	8,000
SIDUFJALL (C4)	4.45 - 4.33	120,000	68	210	3	570	1,770
REVERSE (C5)	4.33 - 4.09	240,000	87	260	3	925	2,750
TOTAL (C2-C5)	4.81 - 4.09	720,000	199	670	3.4	1,075	3,620
NUNIVAK (C 6)	* 4.25 - 4.05	200,000	C.50	C.200	3.6	1,000	4,000
HVÍTÁRSÍÐA				**			
THVERA	4.81 - 4.60	210,000	15	120 (+ 40)	8	1,750	14,000
REVERSE	4.60 - 4.45	150,000	9	80 (+ 40)	9	1,875	16,700
SIDUFJALL	4.45 - 4.43	120,000	6	80 (+ 20)	13.5	1,500	20,000
REVERSE	4.33 - 4.09	240,000	15	155 (+ 5)	10.5	1,500	16,000
TOTAL	4.81 - 4.09	720,000	45	430 (+100)	9.5	1,674	16,000

* Cox (1969). ** Sediment thicknesses in brackets.

and show a southward transgression with time. The early layas (Thvera event) terminate at the north shore of Leirárvogur; those of the overlying reverse event reach south of Leirárvogur, while those of the youngest (Sidufjall) event extend as far south as the southern coast of Akranes. This southward transgression will have been achieved either by a southward shift of the volcanic events or by increased volcanic activity during the Hafnarfjall phase or through the effect of cone building, or by a combination of any of these. The rapid thinning of the succession suggests, that the eruptive sites of the majority of the lavas lay to the north of Leirárvogur, with predominantly southward flow.

The southern flank is anomalous in lacking a flood basalt sequence comparable to that seen north of the central volcano and also for the scarcity of sediments, which do not seem to increase concominantly with the rapid thinning of the lava succession. This conflicts with the conclusions drawn for the succession north of the central volcano (McDougall et al., 1977), which accumulated within the normal zone of rifting, viz. that the "sediments are deposited at approximately the same rate as the lavas in terms of thickness per unit time". This would mean that if a hiatus in lava extrusions occurred on an active spreading ridge, the rifting would continue by normal faulting and fissuring (surface manifestations of dykes at depth (Sæmundsson, 1974)) resulting in the formation of graben structures along the rift zone. Enhanced sedimentation would then occur as is at present taking place e.g. in Þingvellir, SW-Iceland.

Thus it can be concluded that, during the Hafnarfjall phase, rifting may either have been absent or negligible south of the central volcano, and that the lava succession south of Leirárvogur represents an "overflow" of lavas across the southern boundary of the rift zone.

b. Differentiated extrusives

Outside the caldera two rhyolite domes and three intermediate lavas were extruded during the Hafnarfjall phase:

(i) The Rauðhnúkafjall rhyolite dome in northern Leirárdalur is well exposed to the east and west, but screened by later basalts to the north and disected by the caldera fault to the south. It may extend to the southern end of Tungukollur. The dome (c. 600 m thick and 4-5 km^3) was extruded early in the Thvera event and was not buried by the basalt extrusives until near the close of Sidufjall event. In Leirárdalur, a well-laminated rhyolite breccia (> 10 m) wedges out from the dome.

(ii) The Rauðihnúkur rhyolite dome forms an elongated outcrop (5 km, N-S) at the foot of Heiðarhorn in western Skarðsheiði, reaching a maximum thickness of 250 m and a volume of 2-4 km^3. The rhyolite flowed into the (Hafnarfjall) caldera giving the rhyolite outcrops on the western slopes of Snókur, and the laminated rhyolite sediment at the caldera margin (underlying there the tholeiite lava sequence (C4)). To the north the rhyolite divides into two flows; the more extensive of which reaches the southern slope of the basalt cone north of Heiðarhorn. The rhyolite is normally magnetized and from its relationship with the basalts, it can be shown to have erupted during the latter part of Sidufjall event.

(iii) Intermediate extrusives; two flows occur in the Rauðhnúkafjall, one overlying the rhyolite in Svartitindur, and the other resting on the eastern slope of the rhyolite dome near the caldera margin. Both are likely to be of late Sidufjall event age. A third intermediate flow outcrops on Hestfjall and above Brekkufjall and is, as described in a. above and indicated in fig.3.11, of upper Thvera age.

c. The Hafnarfjall caldera

(i) The caldera structure

The caldera, which formed in the Hafnarfjall region towards the end of the Thvera event (i.e. at 4.6 m.y.), consists of three partially intersecting subcircular basins; the Hróar-, the Hrossatungur- and the Snókur basins. The structure measures about 7.5 x 5 km, with a slight NW-SE elongation. The caldera margin is somewhat uncertain in the drift-covered lowlands south of Ölver and in the eastern part of Snókur where it is overlain by later formations.

Although a series of step-faults is suspected to disect the caldera floor, the outer boundary is generally represented by a single fault plane with a throw in excess of 100 m (fig.3.13). Northeast of Hafnardalur, however, two caldera margins are present, where the inner one outlines the subsidences of the individual basins of Hróar and Hrossatungur, the outer one probably represents a simultaneous subsidence of both basinal structures. The only locality where the throw of the caldera boundary can be measured is where the outer boundary cuts the Rauðhnúkafjall rhyolite; here the displacement is about 150 m. However, to judge by the thickness of the caldera infilling, the total amount of the caldera subsidence does not exceed 1000 m.

The Hróar and Hrossatungur basins subsided more or less simultaneously, whereas the Snókur basin in the southeast is slightly younger. All three basins have an accompanying set of cone-sheets,

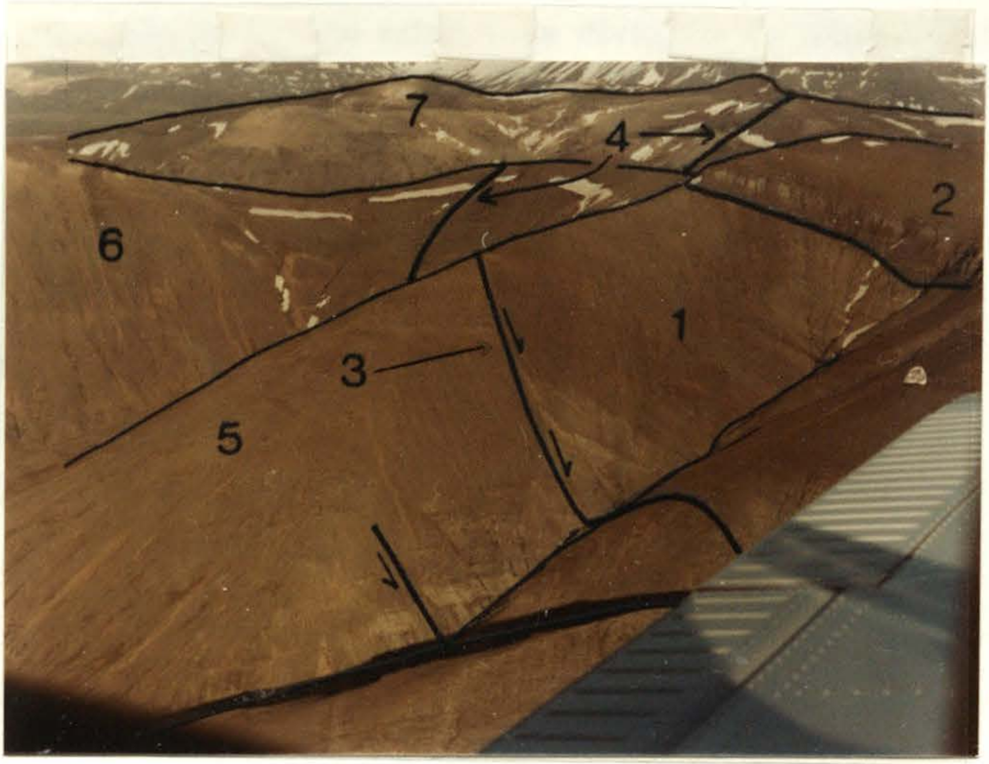


Fig.3.13

The Hafnarfjall caldera fault and infilling in Klausturtunguhóll.
1. The lower basalt unit (1) 2. The lower agglomerate unit (3) 3. and 4. The caldera fault 5. Klausturtunguhóll 6. Tungukollur 7. Rauðhnúkafjall.

where each set converges below the approximate basinal centre as indicated in fig.5.6.

(ii) <u>The caldera filling</u>

The rocks within the caldera are divisible on lithological, compositional and geomagnetic criteria into six units:

1) <u>The lower basalt unit</u>

These basalt lavas occur near the caldera margin in two areas:

a) In Kirkjutunguhóll in the north (fig.3.13) these lower basalts have a thickness of over 200 m with individual flows averaging 2-5 m. They dip 15-35° S with the dips steepest at the base and gradually decreasing upwards. In addition a progressive steepening of the lavas occurs south into the caldera. The lavas have a persistent southward inclination irrespective of the caldera fault alignment, suggesting that lavas flowed into the caldera from the north. The absence of talus breccia at the caldera margin implies a very gradual subsidence of the caldera floor during this episode.

A slightly different relationship to the caldera margin occurs northeast of Hróar where a 3-50 m sequence of 1-3 m thick lavas dip about 50° W to NW into the Hróar basin. Individual flows show a downward gradual disintegration into agglomerate, a feature either resulting from autobrecciation as a consequence of the steepness of the depositional slope or, more likely, flowage into a caldera lake. The transition from breccia to unbrecciated material in each flow at successively higher levels occurs as one ascends the sequence. This may imply a steady deepening of the inferred caldera lake and gradual subsidence of the caldera floor.

b) The basalt sequence inside the southern caldera margin is divisible into a lower and an upper part. The lower one is composed of 5-10 m thick basalt flows and one andesite flow. The upper part (c.50 m) is characterized by distinctly thinner lava flows (1-3 m thick). The strike of the lavas, except where updomed by the Hrossatungur gabbro, is roughly parallel to the complex pattern of the caldera margin in the area. The lower lavas are so thick that it is doubtful if the steep dips could be original flow dips so that post-depositional tilting is probable (as a result of further subsidence of the caldera floor). The thin upper lavas may, however, have their original dips formed from flows running down over the margins of the caldera (like those of Klausturtunguhóll (see a.) above)).

2) <u>The basalt hyaloclastite unit</u>

The next unit within the caldera filling is composed chiefly of hyaloclastites. These provide further evidence for a caldera lake and are believed to have formed during numerous sub-aqueous eruptions. It is likely, that at least some parts of this unit towards the caldera margins are contemporaneous with the lower basalt unit (1), but the central part may be slightly older. The hyaloclastite outcrops chiefly in the S and SW part of the caldera, and floors the whole of the caldera structure. The unit exceeds 300 m thickness northeast of Hrossatungur. Despite lithological variations, the unit is recognizable by its fragmental character, with basaltic clasts rarely exceeding 10 cm across. Apart from some steeply dipping foreset bedding near the caldera margin (e.g. in the east slopes of Leirárdalur) the unit is essentially unbedded.

3) <u>The lower agglomerate unit</u>

This unit, which also consists of hyaloclastite, outcrops mainly in the northern half of the caldera, and attains over 200 m thickness in the Hróar area. It thins rapidly southeastwards against the slopes of the underlying hyaloclastite formation, and only just reaches to the west side of Leirárdalur. It differs from the basalt breccia unit in being coarser with abundant basaltic blocks of up to 2 m in diameter and in a lack of bedding, except for some poorly defined foreset bedding.

Near the base of the unit northeast of Hróar is a sequence of steeply dipping porphyritic basalt flows which grade up into glassy agglomerate. This may have formed as a result of lavas encountering a caldera lake. The scarcity of pillows may have resulted from high flow rates resulting in explosive lava-water interaction. The most convincing example of lava interacting with water is found inside the caldera margin in Rauðhnúkafjall, where an olivine tholeiite compound eruption took place towards the upper boundary of this unit. The simplified E-W cross-section in fig.3.14 illustrates the relationship of the foreset bedding and the overlying lavas, which resembles closely the characteristic lava-hyaloclastite boundaries seen in the Icelandic Pleistocene table-mountains (c.f.Jones, 1970). Unbroken pillows are present, but they are rare. The unit is basaltic in composition with the exception of an acid six unit ignimbrite layer (7 m) occurring within the porphyritic lavas northeast of Hróar.

4) The andesite unit

This unit, which predominantly consists of lavas, reaches a maximum thickness of 500 m in Hróar (fig.3.15) and overlies the basalt lavas and basaltic hyaloclastites in the caldera. It occurs, like the underlying unit, mostly in the northern part of the caldera, and thins like the lower agglomerate unit (3) southeastward against the southern slope of Hafnardalur. While the lavas at the southern slopes of Hafnardalur dip towards the centre of the Hróar basin, a complete

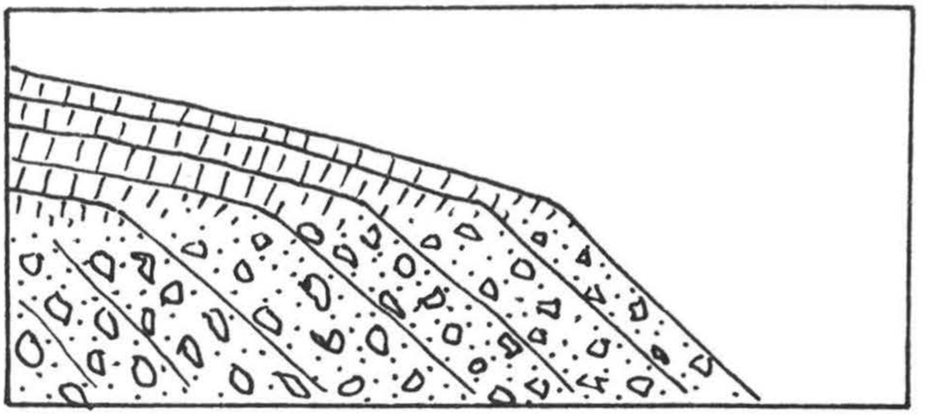


Fig.3.14 A simplified cross section, illustrating the relationship between the lavas and the foreset bedded pillow breccia.

Fig.3.15 The southern face of Hróar mountain.

change in dip direction occurs east across Hrossatungur ridge, which suggests that the formation of the caldera involved two intersecting subsidences (Hróar and Hrossatungur basins).

The lower boundary of the unit is often expressed as a gradual transition from the underlying basaltic agglomerate to andesite lavas. Though the term andesite unit is used, a considerable volume of basalt lavas and hyaloclastites also contribute to this unit; the distinction between andesite and basalt is often obscure in this environment because of the similar glassy appearance of both types. In the NE the unit is predominantly clastic and has abrupt vertical contacts with the lavas, e.g. at the northern end of Hróar. The vertical contacts may imply explosive activity similar to pseudocrater formations, produced when lava runs into shallow water.

A pitchstone ignimbrite (c.10 m) with well flattened fiamme, forms the top of the unit to the northeast, and this may correlate with an ignimbrite in Hesthάls at the lower margin of Sidufjall event (Þóroddsson, 1975).

5) The upper basalt unit

The basalts composing this unit are certainly younger than the andesite unit. They outcrop only on the west slopes of Snókur in Leirárdalur valley. At the caldera margin it is believed to have flowed off the Rauðihnúkur dome, but in the central part of the caldera it rests directly on the basalt breccia unit 1. The dips demonstrate that the lavas flowed into the basin from the south (the Rauðihnúkur rhyolite dome formed an effective barrier to the north and east). Individual lavas, thicken towards the centre of the Snókur basin, giving a maximum thickness to the whole unit of 150-100 m; the exceptional lava thicknesses of 20-40 m of the lowest three flows suggests ponding and the formation of small lava lakes. Due to erosion, the extent of the unit towards the NW is uncertain. Judging by the lack of any evidence for the presence of water, it is likely that the lavas occupied a newly formed basin before any lake developed. Whether this basin formed within an existing caldera structure or whether it represents a new basin, only partially superimposed on the older one, has not yet been resolved. The lavas of this unit are normally magnetized and belong to the Sidufjall event (C 4).

6) The upper agglomerate unit

This unit, the youngest of the formations infilling the Hafnarfjall caldera, overlies the andesite in Hrossatungur (unit 4) and the upper basalt unit (5) in the Snókur basin to the southeast.

In Hrossatungur the agglomerate unit is a coarse, basaltic hyaloclastite, incorporating abundant clasts up to 2 m across and shows a close resemblance to the lower agglomerate unit (3). Occasional poorly defined foreset-beds, dipping 30-50°E suggest eruption sites in the NE part of the caldera.

Agglomerate and pillow breccia involving porphyritic basalts predominate in Snókur together with a few lavas. Columnar-jointed lava lobes also occur, the most spectacular one topping the Snókur mountain (fig.3.16). It is intersting to note that the unit extends SE across the caldera margin implying a level topography in this area adjacent to the caldera margin. The lavas of this unit are reversely magnetized, and are assumed, like the Hrossatungur gabbro, to have extruded after the close of Sidufjall event (C5).

(iii) Discussion

Numerous descriptions of calderas within the axial rift zones, indicate similarity in terms of size, depth and nature of infilling

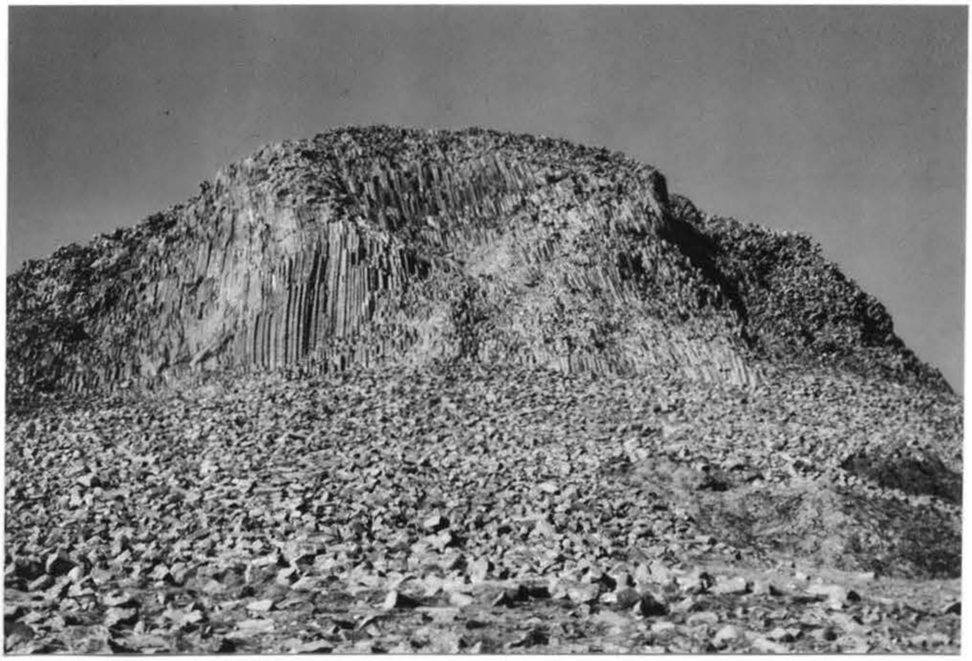


Fig.3.16

A columnar jointed lava lobe (c.50 m thick) in Mt. Snókur.

(e.g. Walker, 1963; Blake, 1964; Sigurðsson, 1966; Sæmundsson, 1972; et al.,1975; Þórarinsson, 1973). Consequently, the fundamental causes controlling their formation may be assumed to be held in common.

Ten caldera subsidences within active central volcanoes can be recognized in Iceland, each of them located within the eastern rift zone. Seven of these are sub-glacial, and have only been positively identified from satellite photographs (Þórarinsson et al.,1973). The other three (Torfajökull (Sæmundsson, 1972), Askja (see e.g. Sigurbjarnarson, 1973) and Krafla (Sæmundsson et al.,1975)) have been mapped in some detail, and, at the time of writing, the last named is currently active, with rifting, seismicity and some minor lava eruptions (Björnsson et al., 1977).

The irregular shape of the Hafnarfjall caldera, due to the intersection of three separate subsidence structures may be analagous to the Askja caldera, which consists of three partially superimposed and individually subsiding basins (Sigurbjarnarson, 1973).

The total subsidence of the Hafnarfjall caldera (800-1000 m) is comparable to those reported for the Stardalur and Reykjadalur calderas (Friðleifsson, 1973; Jóhannesson, 1975).

The pyroclastic rock units, which predominate among the caldera infillings, can often be directly related to interaction between magmas and caldera lakes. The very coarse agglomerate horizons in the Tertiary-age Breiðdalur and Álftafjörður calderas have been interpreted by Walker (1963) and Blake (1964) as having been ejected from explosion craters. However, the lack of lateral size grading within the agglomerate units in Hafnarfjall caldera, the absence of any major sediment horizons outside the caldera, and the breaking up of the glassy porphyritic lavas into fragmental material, favours quiet disintegration of lavas by flowage into a caldera lake.

The porosity and permeability of volcanic rocks in the Neovolcanic zones is high and the percolation of water is consequently rapid (Sigurbjarnarson et al., 1974). The water-table within the caldera and the surrounding area can be assumed, therefore, to keep relatively constant and may be expected to reequilibrate relatively speedily after tectonic or eruptive events as a result of influx of water from outside. The stability of the water-table can be used to assess the process of the caldera subsidence, which, according to the geomagnetic polarity of the rocks in the caldera, remained active for at least 150.000 yrs. The pyroclastic units, overlying the sub-aerial lava horizons, imply that caldera collapse took place by numerous intermittent subsidences. Indeed, the occurrence of such subsidences may be illustrated by;

a) the gradual upward lava-breccia transition of the lower basalt unit (1) as well as the relationship of this unit to the caldera fault in Klausturtunguhóll.

b) The glassy nature of the thick lava sequence of the andesite unit (4). The upper basalt unit (5) flooring the Snókur basin does not, however, show any indication of eruption into or below water; this may be due to a sudden subsidence and subsequent lavafilling of the basin before the water-table had reequilibrated.

It is noteworthy that the average rate of caldera subsidence over 150.000 yrs is 1 m per 150 yrs, a value similar to that for the Þingvellir graben (an axial rift zone feature) during the last 9000 yrs (Tryggvason, 1974).

An important feature of the caldera formation is the relationship between the caldera infilling and the contemporal basalt sequence

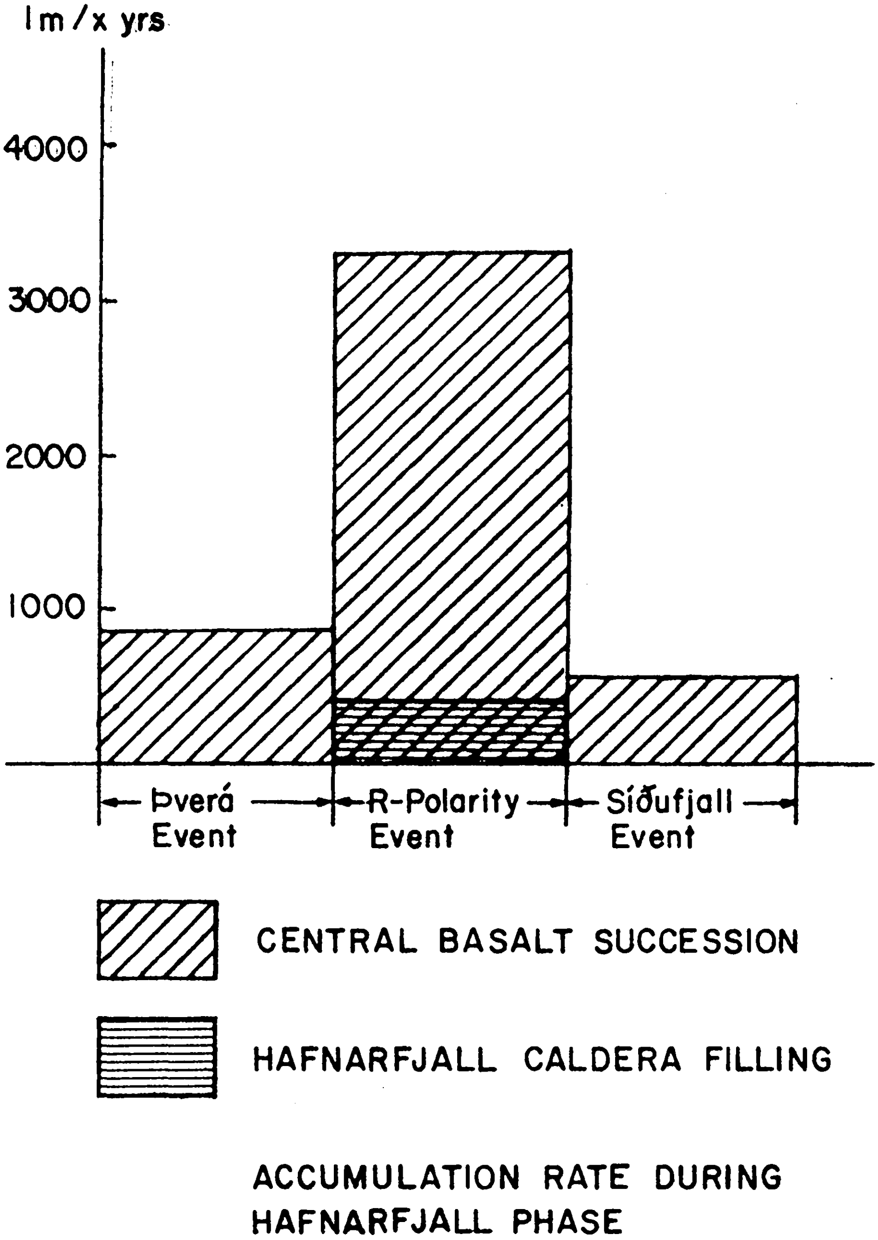

1m / x yrs
4000
3000
2000
1000
Þverá Event
R-Polarity Event
Síðufjall Event
CENTRAL BASALT SUCCESSION
HAFNARFJALL CALDERA FILLING
ACCUMULATION RATE DURING HAFNARFJALL PHASE

Fig. 3.17

within the Central Succession. The histogram (fig.3.17) shows that while the area inside the caldera experienced a anomalously high accumulation rate (c. 1 m : 500 yrs), the surrounding area up to a distance of 10 km from the caldera margin suffered a complementary decrease in the accumulation rate (c. 1 m : 3.300 yrs). This decrease in the accumulation rate within the Central Succession may therefore at least partly be explained by the spatial redistribution of the extrusive activity. Furthermore, an additional volume of magma is likely to be contained in the dense cone-sheet swarms formed during this period. A hypothetical model for calderas is presented in chapter 9.

3.6 The Skarðsheiði phase

a. The Skarðsheiði Tholeiite series

This series reaches its greatest thickness (c.260 m) north of the Kaldárdalur rhyolites. As stated earlier, it directly overlies the thick sediment horizon in Hornsdalur, which was formed towards the close of the Sidufjall event. The series underlies and forms a boundary around the rhyolite extrusives in Skarðsheiði, but is overlain in Geldingardragi by a thick (40-60 m) hyaloclastite horizon, which in turn is overlain by the Reinir compound lava shields. The series thins rapidly out to the west and disappears north of Heiðarhorn, and between there and Skessuhorn it is overlain by the normally magnetized basalt erupted during the Heiðarhorn phase. This westward thinning is mainly attributable to a decrease in extrusion rate in the Hafnarfjall area during this time.

The basalt succession (fig.318) is almost entirely composed of thin tholeiite flows (average thickness 3 m). Sediments are rarely seen. Where basalt lavas bank up against the rhyolites, tuff breccia beds are commonly seen extending out from the latter. Thus a thick rhyolite breccia (> 20 m thick) wedges out from the Mófell rhyolite and thins out to < 10 m within a distance of 1 km, suggesting a talus bank origin (fig.3.19). At a similar stratigraphic level in Hestháls (Þóroddsson, 1975) and Varmalækjarmúli (Smárason, 1975), however, a thin rhyolite breccia occurs with partially collapsed pumice, so that the possibility of a tuff-flow origin of the breccia near Mófell cannot be wholly excluded.

Geomagnetically, the rocks of the Skarðsheiði phase are well-defined as they were extruded almost wholly during the reverse event

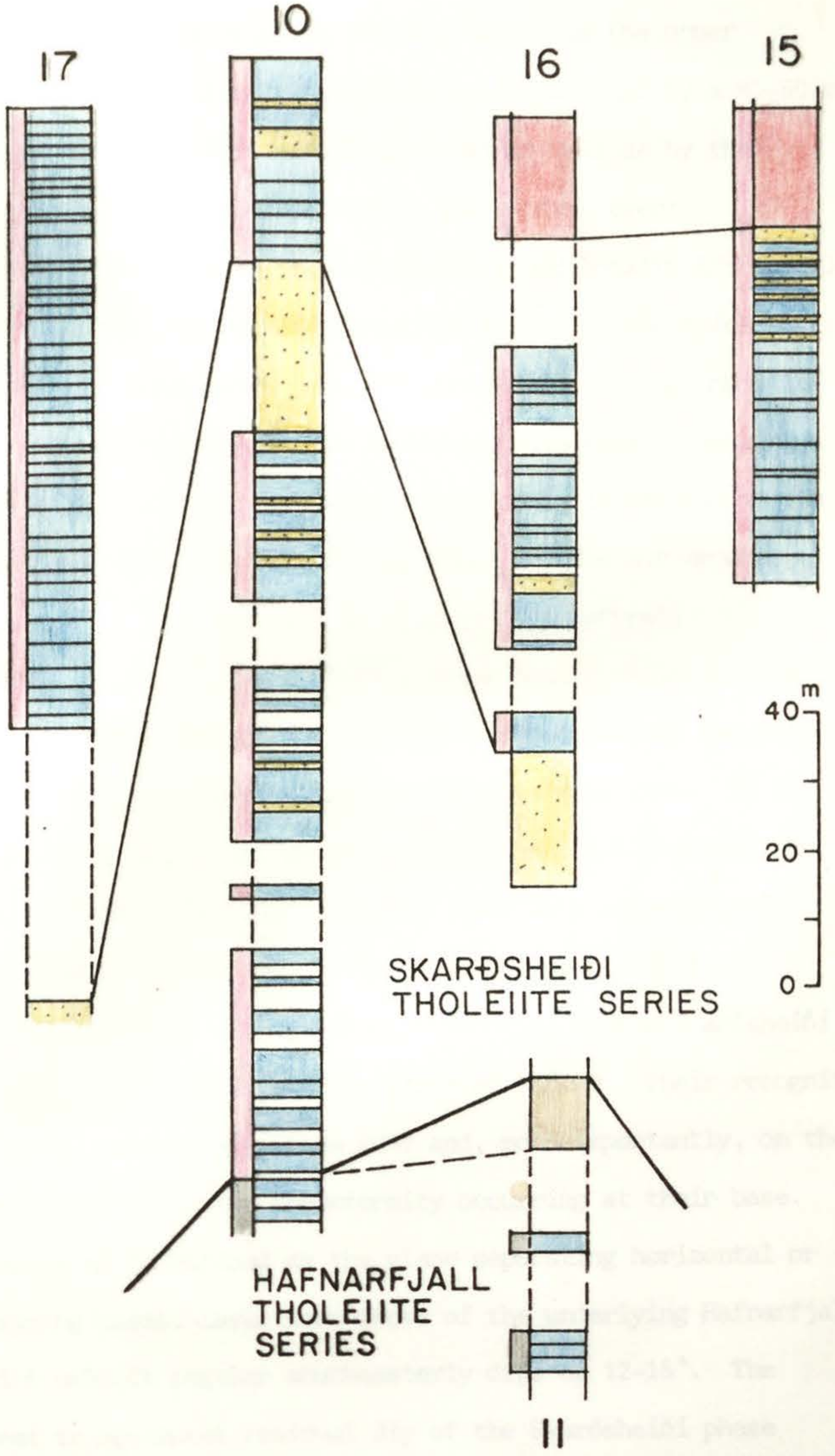

17
10
16
15
40 m
20
0
SKARÐSHEIÐI
THOLEIITE SERIES
HAFNARFJALL
THOLEIITE
SERIES
11

Fig. 3.18

(C5) separating Sidufjall and Nunivak events (4.33-4.09 m.y., McDougall et al.,1977)). Table 3.12 gives an approximation of the lava extrusion rate (1 lava/2.700 yrs) and the lava accumulation rate (1 m/925 yrs). Both must be minimum values as the upper boundary of the series is complicated in Geldingardragi by a 40-60 m thick horizon of porphyritic pillow breccias as well as by the absence there of rocks corresponding to the Nunivak event.

Comparison between the Hvítársíða flood basalts (McDougall et al.,1977) and the Skarðsheiði Tholeiite Series at its thickest, reveals, that the Skarðsheiði area had double the lava accumulation rate and nearly six times the lava extrusion rate (again assuming one lava equals one eruption). This relationship is similar to that between the basalts of the Hafnarfjall phase and the contemporary flood basalts away from the central volcano (see before).

As mentioned above a 40-60 m thick basalt pillow breccia unit formed in Geldingardragi (NE-Skarðsheiði) at the close of the episode during which the Skarðsheiði Tholeiite Series accumulated. It is likely to be of a very local extent, perhaps inside a fault-bounded shallow basin, seeing that no sediments occur in a stratigraphic equivalent basalt sequence to the north (Þóroddsson, 1975).

The exposures of basalts corresponding to the Skarðsheiði phase are very poor on the lowlands south of Snókur. Their recognition is based on the reverse magnetism (C5) and, more importantly, on the identification of the major unconformity occurring at their base. This unconformity is defined as the plane separating horizontal or shallow dipping basalt lavas from those of the underlying Hafnarfjall phase, which exhibit regular southeasterly dips of 12-15°. The shallow west to southwest residual dip of the Skarðsheiði phase

Fig.3.19

A view towards east of the rhyolites in N-Skarðsheiði. 1. Basalt lavas banking up against the Mófell-rhyolite. 2. Andesite lava. 3. Mófell rhyolite. 4. Thick rhyolite breccia horizon. 5. Basalts underlying the Seldalur rhyolite 6. Seldalur rhyolite. 7. Drageyraröxl ignimbrite flows. 8. Skorradalsvatn. 9. Reinir Compound Lava Shield. 10. Skarðsheiði flood basalts.

basalts indicates the derivation and consequential thickening (up to 200 m) towards the east or northeast. This correlates well with the eastward shift of eruptive focus associated with the Skarðsheiði phase relative to that corresponding to the Hafnarfjall phase, and the prominence of the unconformity south of the volcano may be readily explained by the change from the ENE striking fissure eruptions of Hafnarfjall phase to the N to NNW fissure eruptions of the Skarðsheiði phase (see later), thus spatially separating these consecutive phases to the south but not to the north of the volcano.

This pronounced change in fissure (dyke) direction within the central volcano apparently does not affect the overall accumulation rate within the flood basalt region to the north (McDougall et al.,1977), though a decrease in sedimentation coupled with an increase in lava extrusion rate occurred there during this time. On the southern side of the volcano, however, lava accumulation appears to have been largely confined to an area corresponding to an inferred southward extension of the fissure (dyke) swarm associated with the Skarðsheiði phase. This suggests that an effective axial rift zone, equivalent to the one north of the volcano, had still not been established during this time.

b. Differentiated extrusives

The voluminous rhyolite extrusives of the Skarðsheiði phase emerge from under the Skarðsheiði flood basalts between Skessuhorn and Geldingardragi. At least four separate rhyolite eruptions occurred during the phase; two of these early and two late:

(i) Lower rhyolite horizon

The two earlier eruptions gave rhyolite that crop out in the western part of the area, in Mófell (fig.3.19) and Skessuhorn (fig.3.3) and were erupted at about the middle of the reverse event. The basalts banked up against the Mófell rhyolite to the north and northeast and underlay the upper rhyolite horizon to the east. To the west the rhyolite reaches the Skessuhorn before terminating.

The second rhyolite, the Skessuhorn rhyolite, overlies the first rhyolite in Skessuhorn as well as in southern Mófell, though positive identification cannot be made there due to limited exposures. Its eruptive vent probably lies concealed below the flood basalts south of Hornsdalur.

(ii) Upper rhyolite horizon

An eastward shift of eruptive focus occurred at the onset of the upper rhyolite extrusive episode late in the Skarðsheiði phase.

The episode commenced with the formation of the Seldalur rhyolite dome, over 300 m high, just west of Seldalur (fig.3.19). This overlies the Mófell rhyolite and its enveloping basalts, but may predate the Geldingardragi pillow breccia.

The Drageyraröxl rhyolite is the latest acid eruptive of the Skarðsheiði phase (fig.3.20). It will be described here in some detail as it demonstrates the extrusion of viscous rhyolite lava and ignimbrite during a single eruptive event. The eruption commenced with the extrusion of c. 0.5 km^3 rhyolite lava as a dome 300 m high. The width to height ratio of 5:1 shows the lava to have had high viscosity. A sudden change to low-viscosity magma and ignimbrite formation took place at a later phase during the eruption. "Cupola-shaped" multiple cone-sheets, intruded along the base of the rhyolite

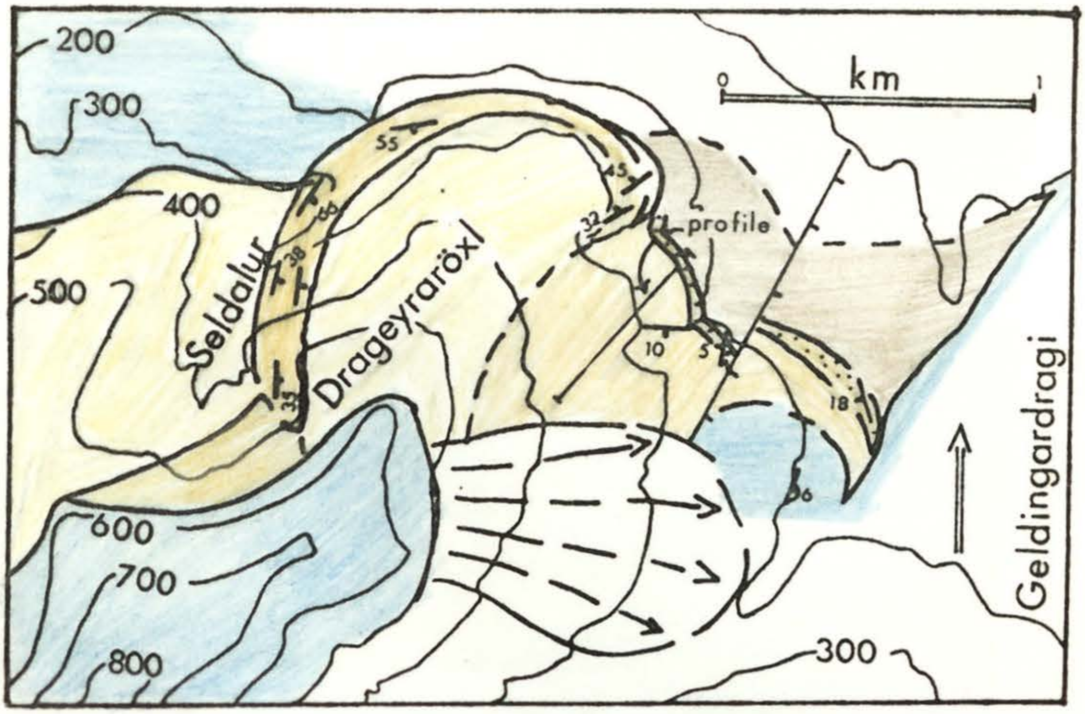


Fig.3.20

A geological map of the Drageyraröxl rhyolite.
Yellow = rhyolite lava, Yellow-brown = ignimbrite
Brown = basalt pillow breccia, Blue = basalt
The profile is shown in fig. 3.24

Fig.3.21 A N-S disection through the Drageyraröxl ignimbrite feeder.
1. Basalt 2. Thick sheets 3. Thin sheets 4. Rhyolite lava.

dome, represent the ignimbrite feeder conduits. The outer boundary of this cone-sheet swarm is marked by a pitchstone unit, up to 6 m thick, except in the northeast, where it had been in contact with partially molten rhyolite lava. The inner margin of the cone-sheet swarm is nowhere chilled against the overlying rhyolite dome. There is a gradual reduction in dip of the sheets from 60-70° in the deepest part of the feeder complex revealed, to 30-40° some 300 m higher up as illustrated in fig.3.20. In northern Seldalur the conduits consist of two groups of cone-sheets distinguished on the grounds of their contrasting thicknesses (fig.3.21). The outer group consists of sheets generally 1-4 m thick, whereas those of the inner group seldom exceed 0.5 m. The number of the sheets in the outer group approximates to the number of ignimbrite flows banked on the eastern slopes of Drageyraröxl. The parallelism of the sheets forming the feeders is striking. So is the absence of any lenses or blocks of country rock or the overlying rhyolite lava within the feeder.

Individual sheets are invariably thoroughly welded with fiamme so flattened and devitrified, that their original pumice structure is unrecognizable (fig.3.22,A), except at the margins of the cone-sheets where flattening is much less prominent. The extreme flattening of the fiamme may be attributed to high flow rates within the sheet as well as to subsequent deformation due to lithostatic pressure from the overlying rhyolite lava dome. Marginal chilling is not observed between sheets; this makes the relatively undeformed fiamme of the sheet margins more satisfactorily explainable in terms of rapid gas exsolution due to friction along the contact planes, together with a corresponding increase in rigidity of the pumice fragments.

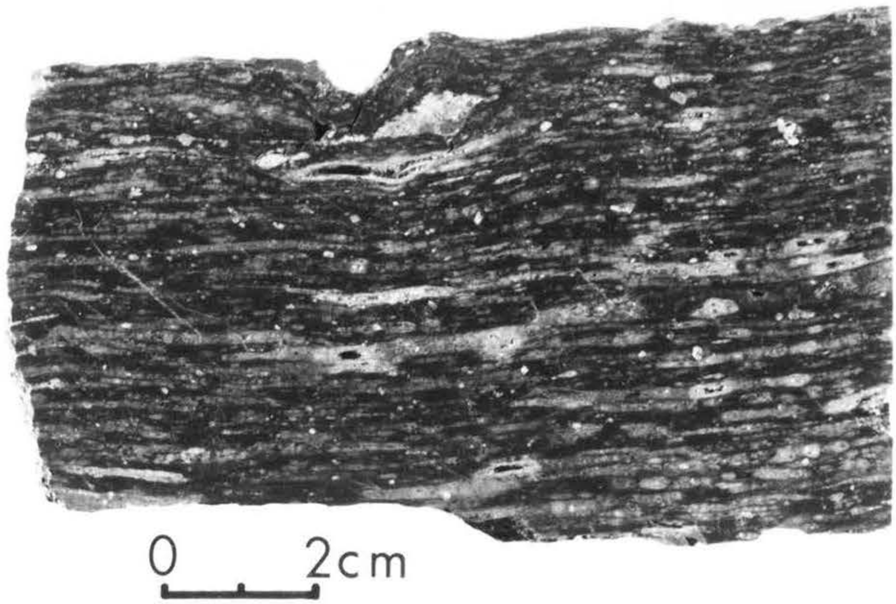


Fig.3.22,A Fiamme structure in the Drageyraröxl ignimbrite plug.

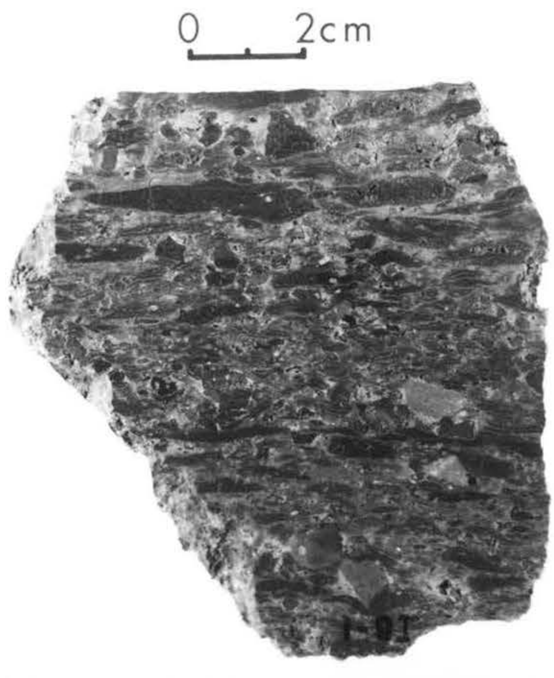


Fig.3.22,B Fiamme structure in the ignimbrite flows in Drageyraröxl.

The intrusion mechanism proposed is schematically illustrated in fig.3.23. The injection of the initial sheet is controlled by the plane of maximum tension created in the rhyolite lava dome by an upward pressure of the gas from exsolving rhyolite magma in the underlying conduit. The successively younger sheets were introduced along the structural planes of weakness provided by the (hotter) central zones of each preceding sheet. Their persistent intrusion along the upper boundary of the preceding sheet may be due to the gradual elevation of the point of maximum tension on the "cupola-shaped" lava-ignimbrite interface. The "pressure-cooker" effect created by the overlying lava-dome provided a further stabilizing effect on the intrusive mechanism; the dome did not allow escape of magma along the conical fracture(s) until a critical pressure (proportional to the weight of the dome) was reached in the underlying conduit. It follows, that after each pressure release attendant upon the injection of a new sheet, a short quiescent interval occurred within which the pressure built up again within the underlying conduit.

The ignimbrite flows on the east and west slopes of Drag-eyraröxl are the sub-aerial equivalents of the feeders. On the east side the flow sequence reaches a thickness of approx. 100 m, of which details of the lower 70 m are shown in fig.3.24; the sequence thins rapidly eastwards against the rising slope of the underlying pyroclastics (c.f.fig.3.23).

A rhyolitic water-lain sediment, often well laminated, separates the ignimbrites from the underlying basalt pillow breccia. This sediment gradually thickens eastwards from c. 4 m near the feeder to about 12 m at the western-side of the gully in Geldingardragi,

Fig.3.23

A probable intrusive mechanism of the Drageyraröxl ignimbrite sheet complex. See text for explanation.

Fig.3.24

The flow thickness of ignimbrite sheets in NE-Drageyraröxl (see profile location in fig.3.20) plotted against their stratigraphic flow number.

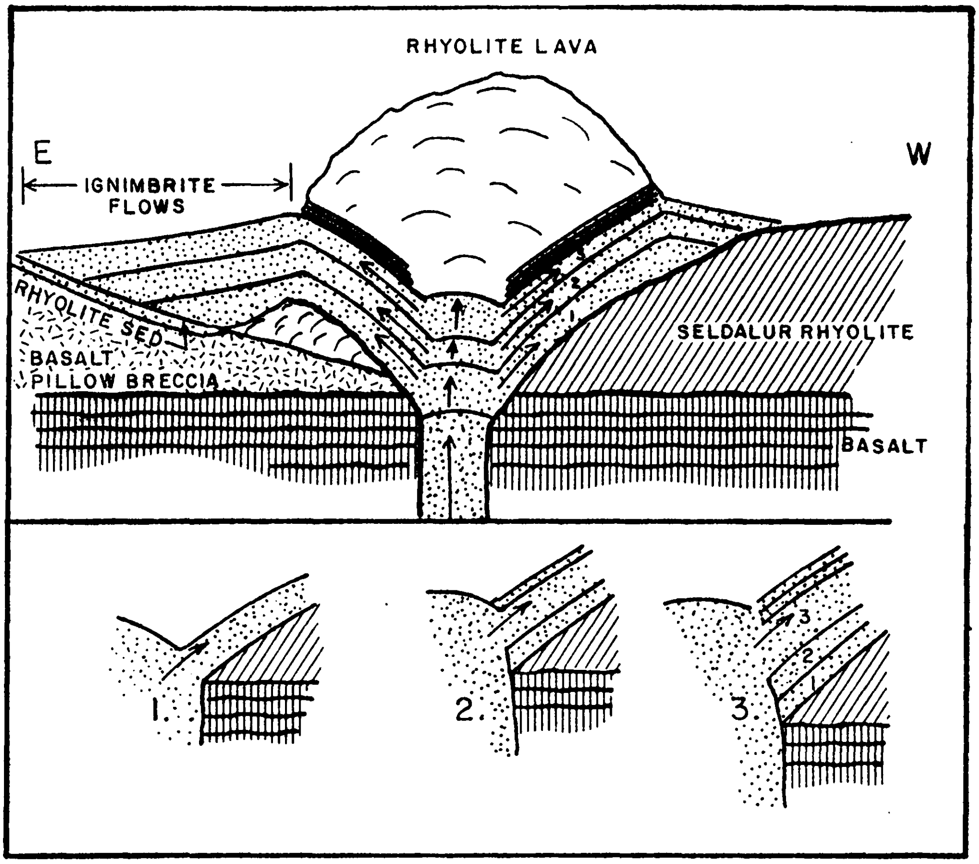


Fig. 3. 23

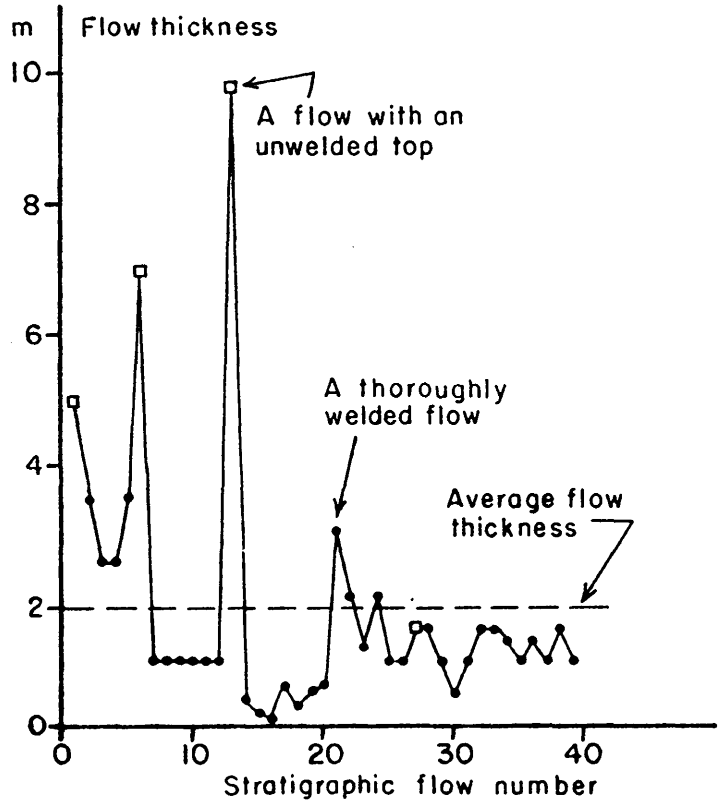


Fig. 3. 24

but thins to 2-3 m on the east side of the same gully. To some extent these thickness variations probably reflect the topography of the environment prior to the rhyolite eruption in Drageyraröxl.

The ignimbrite flow thicknesses in the lower 70 m of the sequence, as shown in fig.3.24, vary from 9 m to 10 cm (average thickness, c.1.8 m). In the whole 100 m sequence it is estimated that there are 50-60 flows in all. Lateral thickness variations within individual flows are not apparent. With four exceptions (fig.3.24) individual flows show good welding from top to bottom and the flattening of pumice is most pronounced in the lower two thirds of each flow where length : thickness ratios of fiammes reach 10:1 (fig.3.22,B). The four exceptional flows (nos. 1, 6,13 and 27) have unwelded tops and the first three are also far thicker (5.7 and 9 m respectively) than those following. These three flows may therefore represent relatively large outpourings of ignimbrite and it is interesting to note they were followed by a period of quiescence (as indicated by their unwelded tops). The overlying flows are usually thin. The interrelationships between flows may indicate a second variable other than that imposed by volatile exsolution in the top of the conduit, such as pulsating action of the magma during its ascent from depth. An overall decrease in eruptive vigour is evident from the diminishing flow thickness fluctuations and from the overall upward thinning of the flows.

The 20-30 m thick ignimbrite horizon within the normally-magnetized sequence in Hesthals (Þóroddsson, 1975) and Varmalækjarmúli (Smárason, 1975) was probably erupted during the Heiðarhorn phase rather than during the Drageyraröxl eruption, as the latter displays a reverse polarity. The absence of stratigraphically equivalent ignimbrite(s) to the north of Drageyraröxl confirms the impression that the ignimbrite(s) were confined to the same tectonic depression as the underlying basalt pyroclastics. The total volume, therefore, is likely to be of similar magnitude to that of other rhyolite eruptions in the area, and each sheet and corresponding flow represents only a pulse of ignimbrite magma whose eruption may have lasted only minutes rather than hours.

The transition from viscous rhyolite lava to fluid ignimbrite within a single eruptive episode is exceptional since ignimbrite eruptions are generally preceded by Plinian phases producing air-fall pumice and are commonly terminated by extrusion of degassed viscous lava (c.f. Ross and Smith, 1961; Tazieff, 1970; Francis, 1976). Fragments of basaltic glass commonly occur as minute xenoliths in the ignimbrite. The lava-ignimbrite transition could well be due to intrusion of a hotter basalt magma into the rhyolite "chamber" at depth, raising the fluidity of the latter by heat and volatile transfer. A similar superheating is well illustrated in the rhyolite component in the composite unit in Brekkufjall. Such a process has also been suggested as a contributing factor in the genesis of the Skessa ignimbrite and the Mælifell caldera ignimbrites in E-Iceland (Walker, 1962; Blake, 1970) and it could be of major importance in the genesis of Icelandic ignimbrites in general.

(iii) Extrusives of intermediate composition are rare and only two andesite lavas were erupted during the Skarðsheiði phase. The 50 m - thick lower flow underlies the rhyolite lavas in Hornsdalur and Skessuhorn and extends at least 2 km further west. The upper flow overlies the basalt sequence, which banks up against the rhyolite dome in Mófell (fig.3.19).

3.7 The Heiðarhorn phase

a. The basalt succession

The central volcanic basalt succession assigned to this phase crops out west of Skessuhorn and in Skarðsdalur (southern Skarðsheiði). During this phase the foci of activity, as indicated by the maximum accumulation of volcanics, moved westwards relative to those concerned with the Skarðsheiði phase.

The stratigraphically equivalent flood basalt sequence extends along the lowlands to the south coast of Akranes.

The Heiðarhorn phase basalts overlie the uneven topography left by the Hafnarfjall and Skarðsheiði phases, and are locally overlain unconformably by the Reinir compound lava shields and the Heiðarhorn Porphyritic Series. In Skarðsheiði the representative profiles (fig.3.25) are only c.2 km apart and separated by the Rauðihnúkur rhyolite dome. The sequence to the north (c.f. fig.3.3) has a thickness exceeding 100 m and consists exclusively of thin (on average < 3 m) tholeiite flows and is devoid of sediments. South of Rauðihnúkur (c.f. fig.3.26) the basalt sequence (> 60 m) consists largely of porphyritic flows 4-5 m thick. Some 50 m of porphyritic lavas are reported to underlie the Reinir Compound Lava Shields in Laxá (Ólafsson, 1976) but their absence to the south in Akranes suggests a relatively localized distribution. The relationship of the porphyritic basalts to the tholeiites to the north is uncertain but it is assumed that the porphyritic basalts overlie the latter. If so, the combined sequence may reach up to 200 m in thickness.

In Akranes, the corresponding flood basalt sequence (which is largely composed of tholeiite lavas) is estimated to reach a thickness of 100 m or more (fig.3.25). Variations in dip and strike

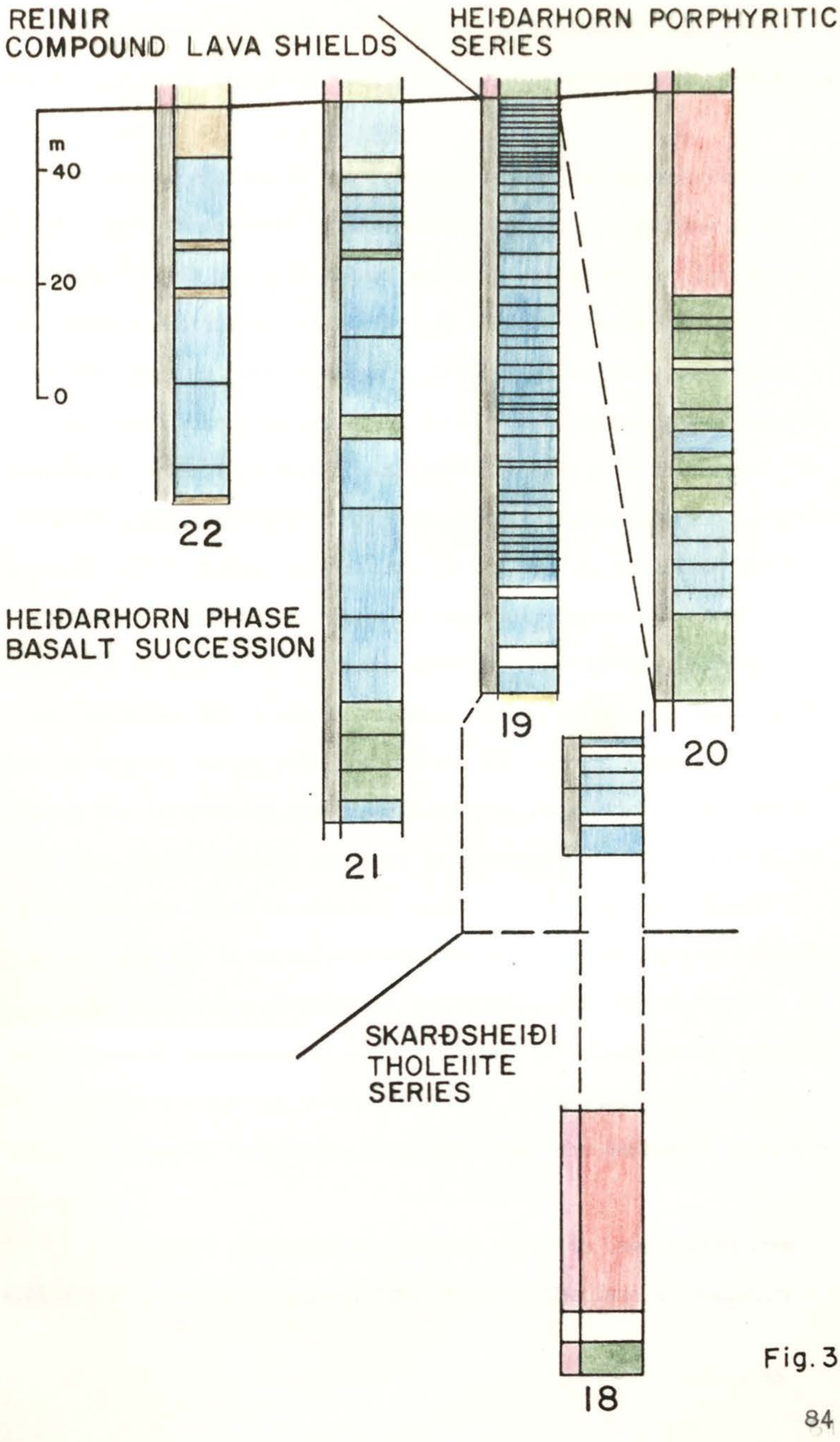

REINIR
COMPOUND LAVA SHIELDS
HEIÐARHORN PORPHYRITIC
SERIES
m
40
20
0
22
HEIÐARHORN PHASE
BASALT SUCCESSION
19
20
21
SKARÐSHEIÐI
THOLEIITE
SERIES
18

Fig. 3.25

occur in the lower part of this sequence and are most notable on the south coast where the lavas are near horizontal or dip very gently towards the S and SE, which indicates that the sequence may terminate a few kilometers off the south coast.

The correlation of the normally magnetized Heiðarhorn phase basalts, with those north of the research area, is complicated by uncertainities in magnetic polarities of lavas as well as by unusual lava characteristics in the north. In Varmalækjarmúli, about 15 km NE of the research area, (Smárason, 1975), the normally magnetized sequence, most likely to correlate with the Heiðarhorn phase basalts, consists of seven tholeiite flows totalling c.80 m in thickness. In Hvítársíða, still further north, the normally magnetized succession is nearly 200 m thick, and consists mostly of thin tholeiite flows, which continue upwards into 80 m of reversely magnetized flows (McDougall et al., 1977). On the basis of K/Ar-datings, McDougall et al. regarded this normally magnetized succession as consisting of basalts erupted during both the Nunivak and Cochiti events but without the intervening reverse event. The suggestion (Jóhannesson, 1975) that the Hvítársíða sequence is a component of the Skarðsheiði central volcano flank is unlikely because; a) the thick basalt flows of same age in Varmalækjarmúli between the two regions (Smárason, 1975) indicate a division in topography, b) the continuity of the Heiðarhorn succession favours a single lava accumulation episode (i.e. during the Nunivak event), and c) the accumulation of thin tholeiite flows in Hvítársíða continued after the demise of the central volcano.

Cox (1969) estimated the Nunivak event to have lasted from 4.25 - 4.05 m.y., i.e. approx. 200.000 yrs. The lava accumulation

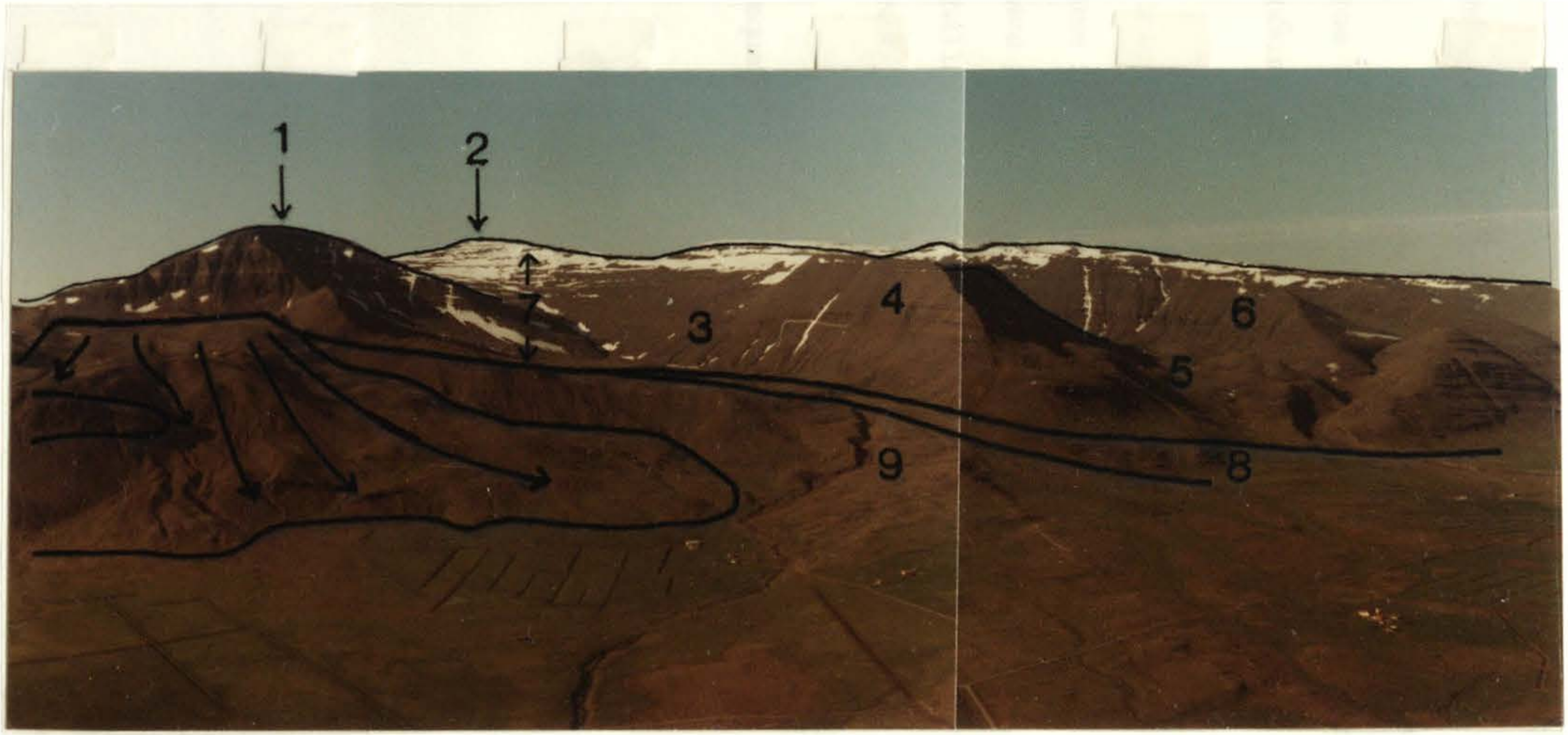


Fig.3.26 A view towards the southern slopes of Skarðsheiði

1. Skarðshyrna 2. Heiðarhorn 3. Skarðsdalur 4. Tungukambur 5. Súlárdalur
6. Þverfjall 7. Hvalfjörður lenticular lava pile 8. The Reinir compound lava shield
9. Heiðarhorn phase basalt succession 10. A recent landslide

rate of the Heiðarhorn phase therefore is estimated to have been around 1 m per 1000 yrs, or one lava each 4000 yrs (table 3.12).

b. Differentiated extrusives

Three lavas of differentiated composition occur within the Heiðarhorn phase sequence:

1) A small pitchstone lobe borders the Rauðihnúkur rhyolite dome to the west and directly overlies the caldera unit 6 in the Snókur basin.

2) A 30 m thick andesite lava banks up against the southern slopes of the Rauðihnúkur rhyolite dome to the southeast. Where its base rests on the pyroclastics, the andesite flow displays large lava pillows exhibiting radial jointing. Both lavas have flowed into shallow water, and were extruded near the onset of the Heiðarhorn phase.

3) A 20-30 m thick andesite lava overlies the Skarðsdalur sequence and was extruded towards the close of the Heiðarhorn phase.

3.8 The Reinir Compound Lava Shields

This compound lava succession extends from the south coast of Akranes, along the west and north slopes of Akrafjall and to Skarðsheiði in the north.

In Akranes and southern Skarðsheiði the succession overlies the Heiðarhorn phase basalts but banks up against the Skarðsheiði rhyolites in northern Skarðsheiði. The succession is overlain by the Heiðarhorn Porphyritic Series.

The succession is largely composed of two compound lava shields, the lower one solely confined to Akranes whereas the upper shield extends from Akranes to Skarðsheiði in the north. The representative profiles of the succession are shown in fig.3.27.

The lower shield is only exposed in Akranes where it is separated from the underlying lavas (one tholeiite and three or four olivine tholeiite flows) by a sandstone horizon up to 3 m thick. The compound lava shield thickens southward from c.35 m in Kjalardalur to c.50 m above Reinir farm. The centre of the shield may lie to the south or southeast of Reinir farm.

The upper shield is separated from the lower one by a 3 m thick sandstone and a thick tholeiite flow. The compound lava shield thickens from 70 m above Reinir farm to 80 m in Kjalardalur and may reach 100 m at the base of Tungukambur on the south side of Skarðsheiði before wedging out northwest against the slope of the Heiðarhorn phase basalts (fig.3.26). This shield reappears in southern Kaldárdalur (c.30 m thick) and SSW of Mórauðihnúkur (c.15 m), and at both locations it banks up against the southern slopes of the rhyolite domes (fig.3.19). In Geldingardragi it overlies the basaltic pillow breccia unit and the Drageyraröxl

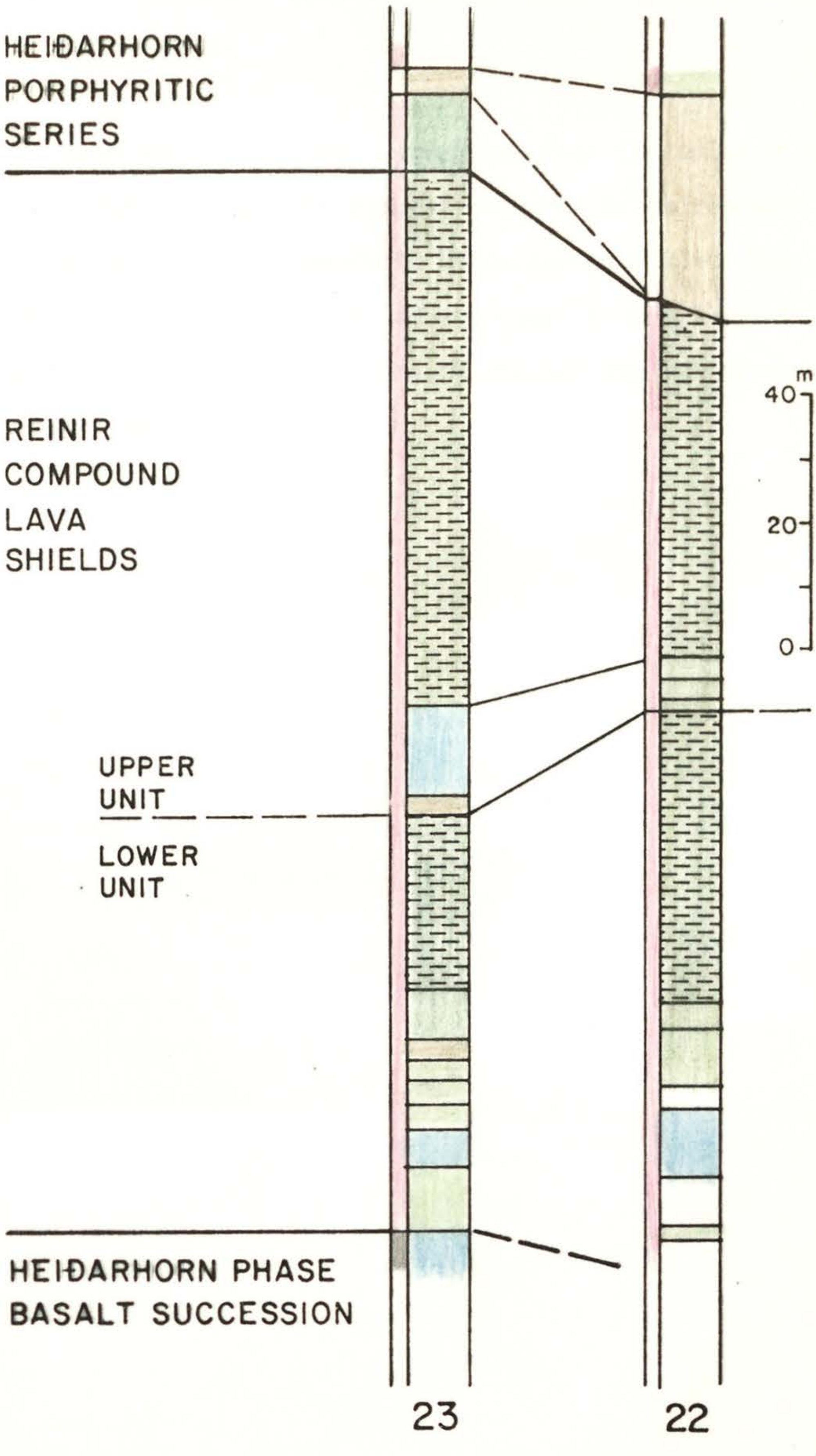

HEIÐARHORN
PORPHYRITIC
SERIES
REINIR
COMPOUND
LAVA
SHIELDS
UPPER
UNIT
LOWER
UNIT
HEIÐARHORN PHASE
BASALT SUCCESSION
40 m
20
0
23
22

Fig. 3.27

ignimbrite. The upper shield lava succession thickens towards the SE margin of Skarðsheiði and it is probable that the eruptive centre lay in this locality.

These shield volcanoes accumulated after the demise of the central volcano, and are the youngest eruptives in the research area of the Hafnarfjall-Skarðsheiði lenticular lava unit. They both show reverse magnetization and are likely to have erupted during the reverse event separating the Nunivak and Cochiti events at 4.05-3.92 m.y. (Cox, 1969).

CHAPTER 4

THE HVALFJÖRÐUR LENTICULAR LAVA UNIT

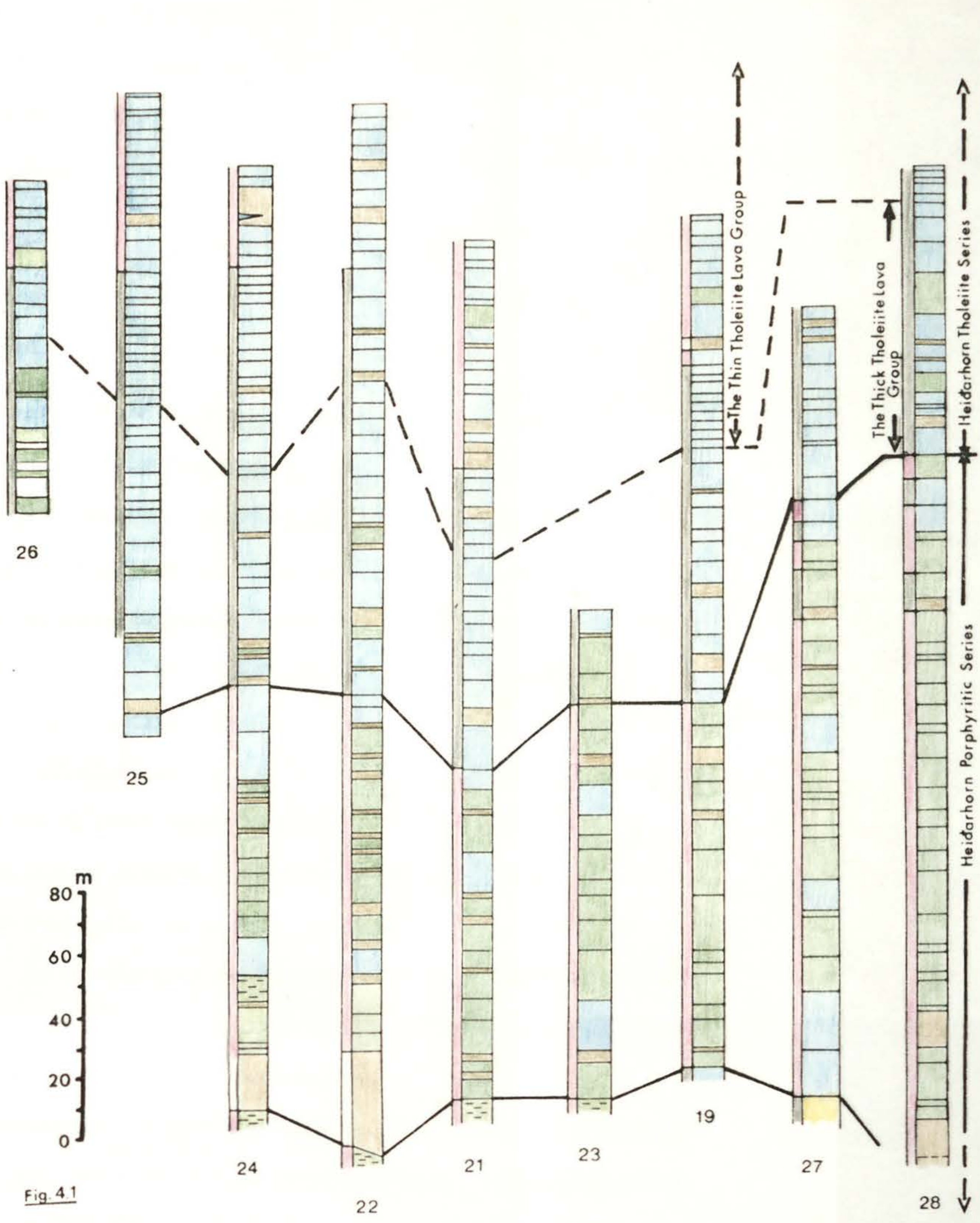
The basalt succession discussed below composes the west and southwest parts of the Hvalfjörður lenticular lava unit, whose centre coincides with the Hvalfjörður central volcano. It forms the principal part of Akrafjall and the upper part of Skarðsheiði. (c.f. fig.3.3 and 3.26).

The succession shows a gradual increase in dip southeastwards towards the central axis of the lava unit (from 3° at the top of Heiðarhorn to 8° in Súlardalur in southern Skarðsheiði). The dip increase is accompanied by a thickening of the constituent lava units. Similar relationships have been recorded in the Tertiary lava successions of E-Iceland (Walker, 1960).

Profiles of the succession are shown in fig.4.1. It is divisible into two series; an earlier porphyritic series (Heiðarhorn Porphyritic Series) and a younger aphyric series (Heiðarhorn Tholeiite Series).

4.1 The Heiðarhorn Porphyritic Series

This series is exposed both in Akrafjall and Skarðsheiði where it overlies the Reinir compound lava shields and also the Drageyraröxl, Skessuhorn and Rauðihnúkur rhyolites. In Akrafjall the series is separated from the Reinir Compound Lava Shields by a fluviatile conglomerate (over 30 m thick), overlain by 3-4 olivine tholeiite lava flows (c.30 m thick). The top of the series is defined by a change from porphyritic flows to aphyric tholeiites; this change also approximately coincides with the geomagnetic reversal



26
25
24
22
21
23
19
27
28
80 m
60
40
20
0
The Thin Tholeiite Lava Group
The Thick Tholeiite Lava Group
Heidarhorn Tholeiite Series
Heidarhorn Porphyritic Series

Fig. 4.1

(Gilbert-Gauss) in the area. The phenocrysts are mainly plagioclase with subordinate amounts of clinopyroxene (mostly microphenocrysts).

The following thicknesses and flow numbers have been recorded:

locality	thickness (m)	no. of flows
S- & W-Akrafjall	90	11
Kjalardalur (N-Akrafjall)	120	13
Heiðarhorn	120	13
Skessuhorn	190	24
Þverfjall	200	31

The average flow thickness is about 7 m. Although the thickness variance can, to certain extent, be attributed to the uneven topography under the series (e.g. it is thinner above the rhyolite domes in Drageyraröxl, Skessuhorn and Rauðihnúkur) there seems to be a definite increase in thickness southeastwards as the centre of the lenticular lava unit in Hvalfjörður is approached, reflecting greater eruptive rates in that area. An indication of this increased effusion rate is provided by the geomagnetic polarity transition at the Gilbert-Gauss boundary. In Akrafjall and Heiðarhorn the transition occurs between two consecutive flows, whereas in Skessuhorn and Þverfjall the transition spans five and six flows respectively. In Hestdalsöxl at the eastern end of Skarðsheiði, the magnetic irregularities at this boundary are reported to span 11-12 flows (Wilson et al.,1972; G.I.Haraldsson,1975).

The Heiðarhorn Porphyritic Series thins towards the northeast along the volcanic zone to 70 m in Reykholtsdalur (Albertsson,1971), and to 55 m in Hvítársíða about 30 km northeast of Skarðsheiði (Jóhannesson, 1972)

Sediments are common between the lava flows and may reach over 30 m in thickness. Their distribution within the series, however, varies in space and time. In NW-Akrafjall, Heiðarhorn and Skessuhorn they only constitute 4-7% of the succession whereas in S- and NE-Akrafjall and S-Skarðsheiði the sediments form 15-25%. At these latter locations the sediments are most pronounced towards the base of the series. The increasing sediment proportion eastwards along the base of the series is, along with the apparent absence of any representatives of the Cochiti event from the succession, an indication of relatively low extrusion rates during the infancy of the lenticular lava unit.

4.2 The Heiðarhorn Tholeiite Series

This lava series forms the top of the basalt succession in Akrafjall and Skarðsheiði. It overlies the porphyritic series and marks the onset of the normally magnetized Gauss epoch. The upper limit is arbitrarily set by the erosion level in the research area. The profiles in fig.4.1 give a fairly accurate account of the series. The maximum thickness of the series is about 150 m in Akrafjall.

The series is divisible into two groups on the grounds of contrasting lava thicknesses:

a. The thick tholeiite lava group

This group consists principally of tholeiite lavas, except in Grafardalur (SE-Akrafjall) where a couple of olivine tholeiite lavas occur near the base. The thickness of the group varies from 64-93 m (9-11 flows) with an average flow thickness of 6.5 m (i.e. a little less than in the underlying porphyritic series).

The lavas commonly contain sporadic (micro)phenocrysts (plagioclase, pyroxene, olivine). Sediments within the group make up between 8-13% of the succession.

b. The thin tholeiite lava group

This group is easily distinguishable from the lower one in having markedly thinner lava flows. The average flow thickness is c. 4 m, i.e. 2.5 m less than the average in the "thick tholeiite group" beneath. The lower boundary is sharply defined in Skarðsheiði, but in Akrafjall can only be defined to within 2-3 lava flows. The maximum thickness is approximately 100 m in the eastern part of Akrafjall.

Predominantly the lavas are nearly aphyric tholeiites except for some porphyritic lavas (1-6 flows) in the upper part of the group in eastern Akrafjall.

About 40-60 m above the base of the group there is a geomagnetic reversal to a reversely magnetized lava flows of the Mammoth event (3.06 m.y. (Cox, 1969)). The upper boundary of the Mammoth event is above the erosional level in the research area, but in SE-Akrafjall the lavas attain a minimum thickness of 75 m during this event.

The percentage of sediment from profile to profile shows much greater variation (0.5-18%) than in the underlying "thick tholeiite lava group". The main cause of this fluctuation is the 3-22 m thick conglomerate horizon of unique origin. Excluding this horizon, the variation narrows down to 0.5 - 6%, which is about half the proportion seen in the underlying unit. The conglomerate mentioned above is an important stratigraphical marker. It is found on both Akrafjall and Skarðsheiði and occurs one to three lava flows above the lower boundary of the Mammoth event lavas. In western Akrafjall, the thickness varies from 15-22 m and on southern

Akrafjall it measures 15 m but wedges out and disappears in Grafardalur to the southeast. In Heiðarhorn it measures 4 m. The sediment is principally a coarse fluviatile conglomerate. Two features distinguish it from the common Tertiary sediments;

a) the very large size of the boulders, which in places reach up to 1.5 m.

b) the grey colour of the lowest part of the sediment in western Akrafjall.

It has been argued that both these features are indicative of glacial origin (Gunnlaugsson et al.,1972). Perhaps the strongest evidence of a glacial origin for this sediment is the widespread occurrence of a distinct sediment along the same stratigraphic level. Thus a thick sediment occurs southeast and east of Skarðsheiði (Sæmundsson, pers.comm.) and has also been traced northeast to Reykholtsdalur and Hvítársíða where glacial striations are to be found on the surface of the underlying basalt flow (Sæmundsson and Horst, 1974). In Jökuldalur, in E-Iceland, a tillite horizon occurs at the same geomagnetic boundary (Wensink, 1964; Watkins et al., 1975). It seems, therefore, likely that this sediment in the research area is equivalent to the lowest tillite horizon found on a regional scale in Iceland and marks the onset of Quaternary Period.

CHAPTER 5

INTRUSIVE ROCKS

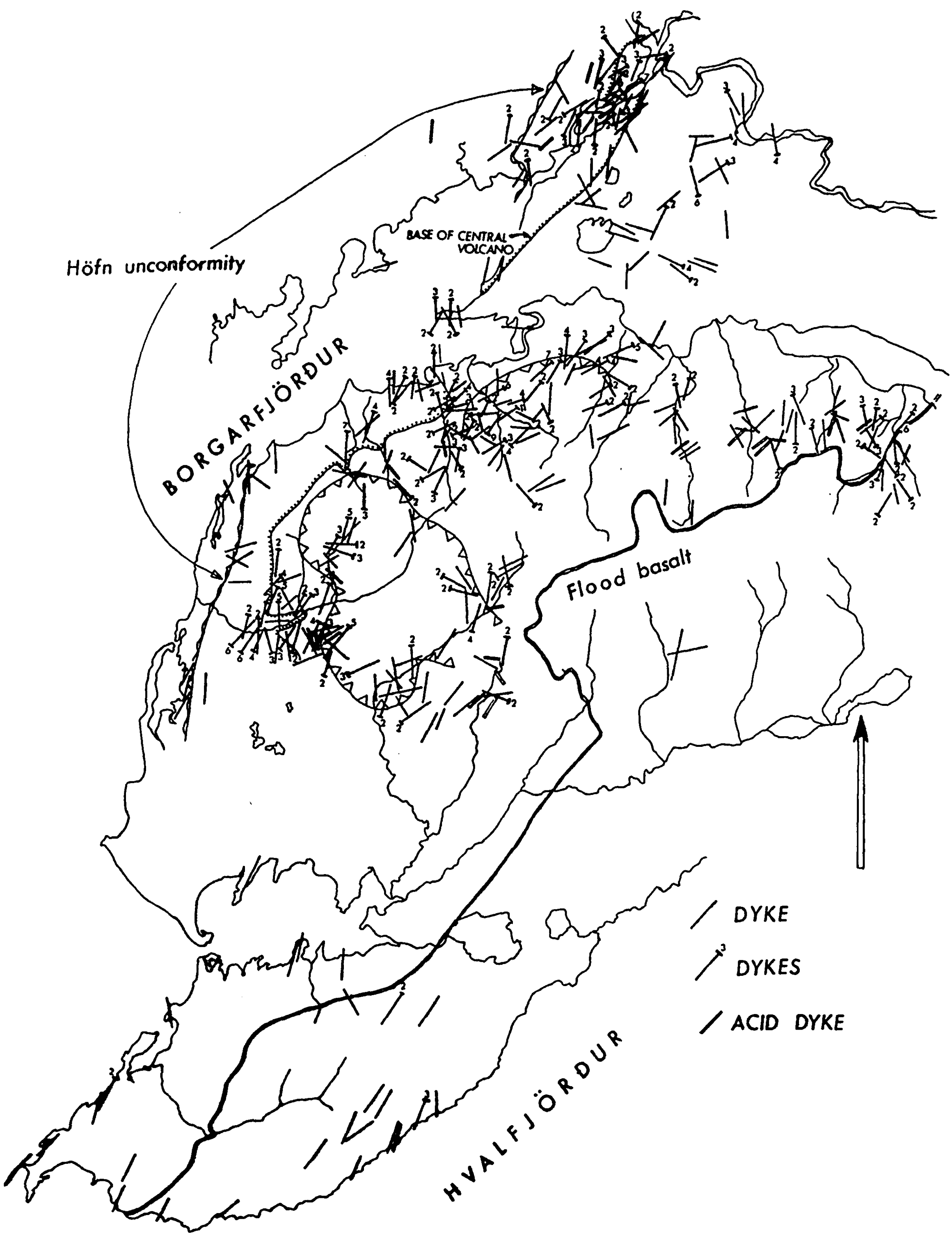
5.1 Dykes

The lenticular shield-like structure of the lava pile with the siting of a central volcano at its focal point has been pointed out by Gibson (1966) and Gibson and Piper (1972). This structure is the result of prolonged rifting within a localized sector of the axial rift zone, as evidenced by the associated dilational dyke swarm (Walker, 1963). The correlation between the dyke-swarms of eroded regions and the fissure-swarms (eruptive and noneruptive) associated with active central volcanoes along with their slightly oblique arrangement to the direction of the axial rift zone has been noted (Sæmundsson, 1974). This slightly oblique arrangement is also evident in the dyke swarms (Jóhannesson, 1975). Each swarm attains maximum intensity in the core of the central volcano (Walker, 1963). Dyke intensity is also a function of depth since 100% dilation is perhaps reached at the upper boundary of layer 3 (e.g. Gibson and Piper, 1972; Pálmason, 1973; Friðleifsson, 1973).

Nearly 700 dykes were located and mapped in the research area (fig.5.1). Their thicknesses vary from less than 0.5 m to over 10 m, but the average thickness is 1.6 m and the greatest thickness frequency is 1 m (fig.5.2,B). No correlation has been observed between thickness and trend. They occur at right angles to the lava flows and were intruded prior to the tilting of the volcanic succession.

Two dyke-swarms are present in the research area; a. an earlier swarm contemporaneous with the Hafnarfjall-Skarðsheiði lava pile, and b. a younger swarm contemporaneous with the overlying flood

Fig. 5.1



Höfn unconformity
BASE OF CENTRAL VOLCANO
BORGARFJÖRDUR
Flood basalt
HVALFJÖRDUR
DYKE
DYKES
ACID DYKE

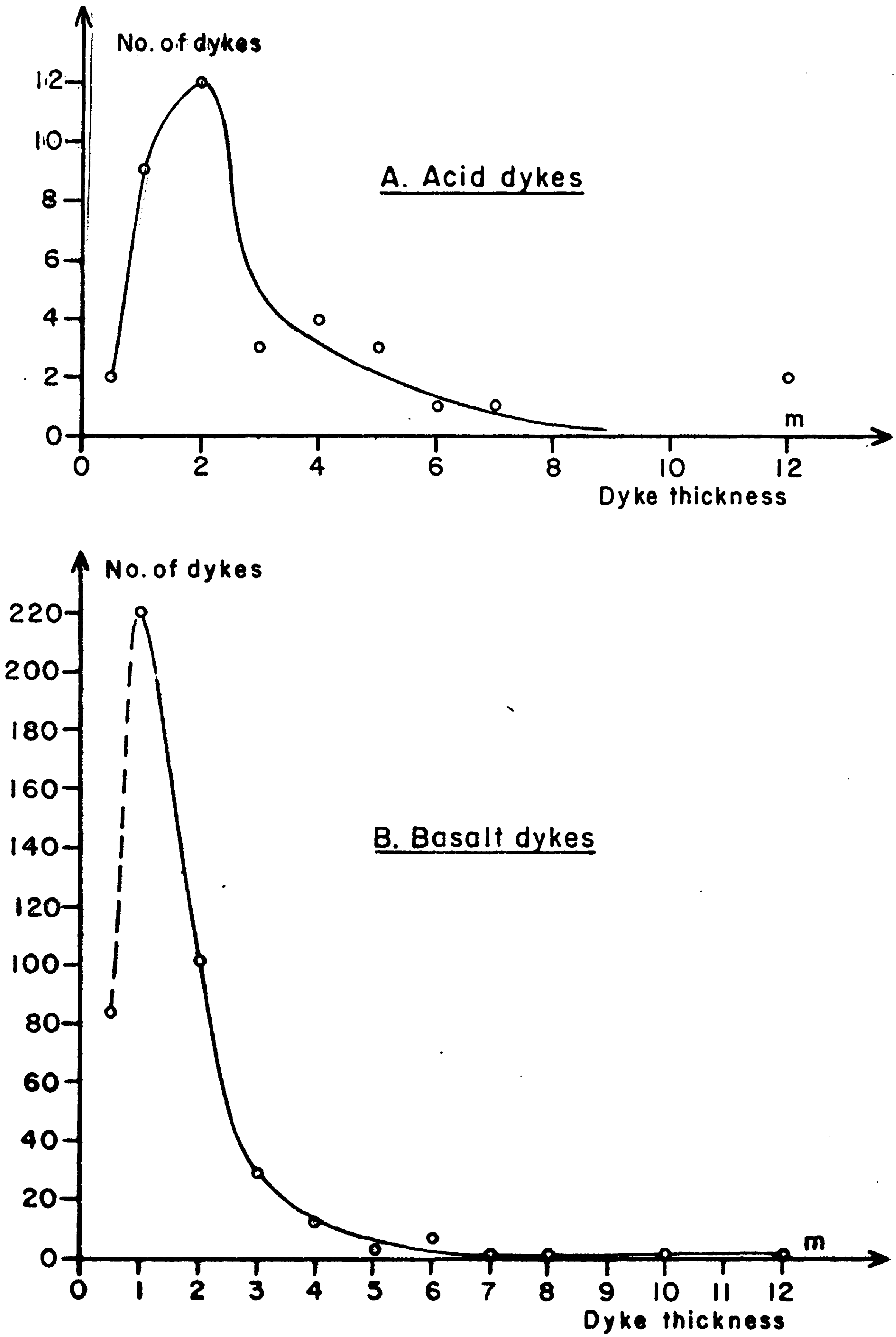


Fig. 5.2. Number and thickness of A. acid dykes and B. basalt dykes in the research area.

basalts.

a. The Hafnarfjall-Skarðsheiði dyke-swarm

Compared with the dyke-swarms associated with the Hvalfjörður and Esja central volcanoes (Gunnlaugsson et al.,1972; Friðleifsson, 1973) which followed in age within the same axial rift zone, the Hafnarfjall-Skarðsheiði dyke-swarm is anomalous with respect to direction variation and asymmetrical distribution about the volcanic centre.

The dyke-swarm is divided into four components based on dominant direction, areal distribution and age:

1) NNE-NE dykes. Dykes with this trend dominate the western edge of the area, and are confined to the zone between the Höfn unconformity and the Ölver-Hvítá flexure (figs.5.1 & 5.3). A sudden drop in dyke intensity occurs just east of and parallel to the Höfn unconformity, from 7 per cent dilation west of Ölver and about 5 per cent in Hvítá to less than 1 per cent dilation in the adjacent areas to the west. Dykes with these trends probably fed the Hafnarfjall Olivine Tholeiite Series, the extrusives of Brekkufjall Phase as well as the Leirárvogur flood basalt succession. Dykes in this category are prominent throughout the research area.

2) NE-ENE dykes. This group is well-defined in time and space and is mainly confined to a c. 15 km wide NE-ENE zone between the Hvítá-Grímsá intersection to the north and the Snókur area to the south (figs.5.1 & 5.3). It has also been noted in the western part of Hvítársíða (Jóhannesson, 1975) about 20 km NE of the research area. The western boundary of this dyke trend coincides with the Ölver-Hvítá flexure.

Two lines of evidence suggest that these dykes fed the

Fig.5.3

Rose orientation diagrams of dykes in the research area.

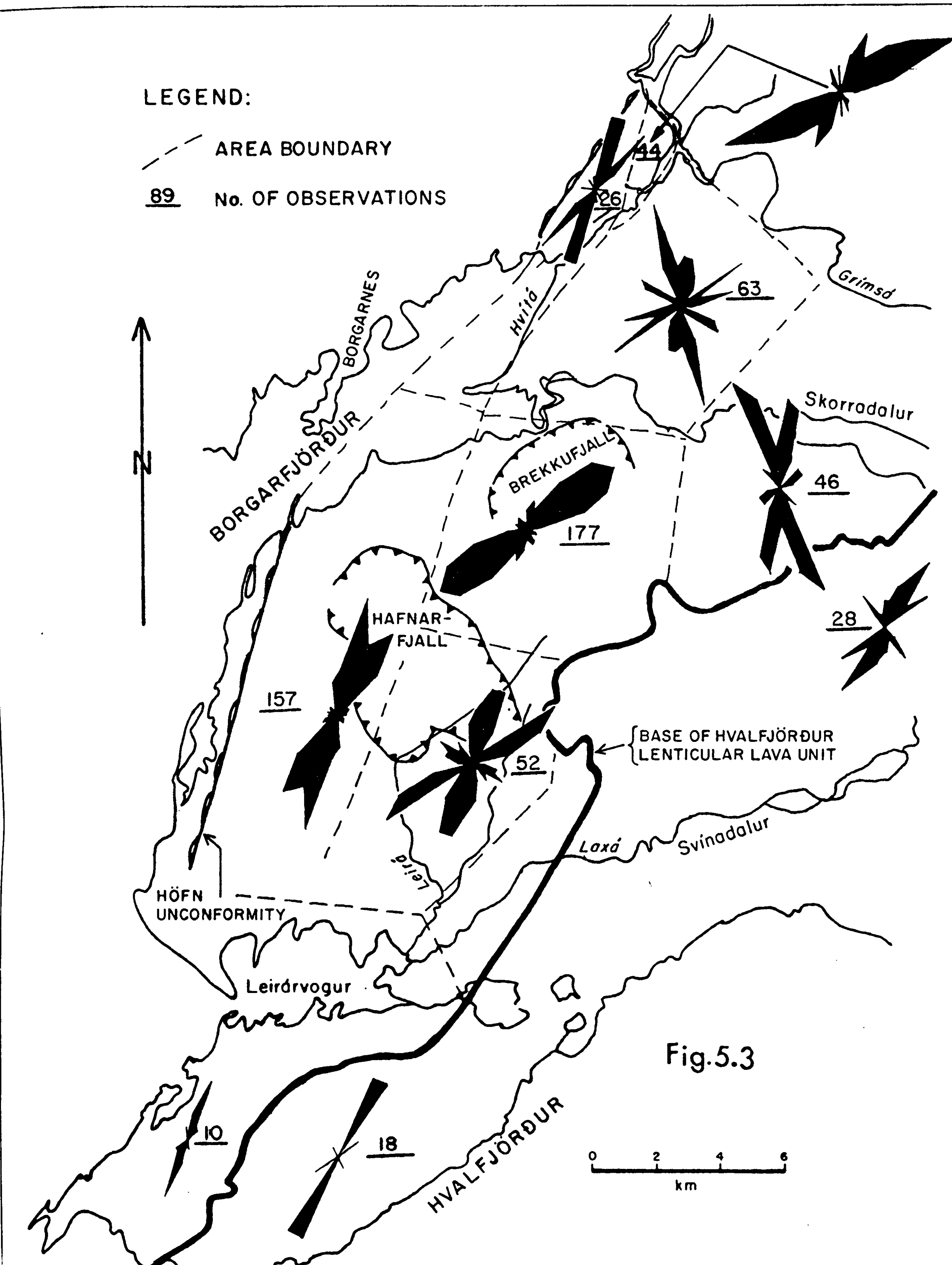

LEGEND:
AREA BOUNDARY
89 No. OF OBSERVATIONS
N
BORGARNES
BORGARFJÖRÐUR
Hvítá
Grímsá
Skorradalur
BREKKUFJALL
HAFNARFJALL
BASE OF HVALFJÖRÐUR LENTICULAR LAVA UNIT
Laxá
Svínadalur
Leirá
HÖFN UNCONFORMITY
Leirárvogur
HVALFJÖRÐUR
44
26
63
46
177
28
157
52
10
18
0
2
4
6
km

Fig.5.3

Hafnarfjall extrusives;

a) The highest intensity of these dykes occur in the volcanics associated with the Brekkufjall phase (up to 5 per cent dilation) while they become relatively scarce towards the upper part of the volcanics erupted during the Hafnarfjall phase.

b) The disappearance of these dykes towards the south coincides with a rapid thinning of Hafnarfjall phase extrusives. The absence of intrusives south of Hafnarfjall is also indicated in fig.5.4 by the monotonous aeromagnetic field (Sigurgeirsson, 1975) and the anomalously low gravity values (Pálmason, 1974) (fig.5.5).

3) N-NNW dykes. Dykes with N to NNW trend are dominant in the eastern part of the area and represent the intrusive equivalent of the Skarðsheiði extrusives. These dykes are well developed in the Andakíll lowlands but are scarce west of Hvítá, as is the case of the NE-ENE dykes (described above). The eastward thickening of the lava succession (C5) above the unconformity on the Akranes lowlands, suggests that these dykes continue to the south below the flood basalt succession (see chapter 3).

4) NW-WNW dykes. Dykes showing a NW-WNW trend are present but insignificant throughout the research area. Their relationship to the central volcano is uncertain except in the Snókur area where dykes of this direction (along with a few NNE trending dykes) cut through the Skarðsheiði phase volcanics (C5) and where probable dyke-feeders of the Heiðarhorn phase intermediate extrusives occur.

Acid dykes.

About 30 acid dykes were mapped in the area, mostly within the core of the central volcano. In general their trend is similar to that of the contemporaneous basalt dykes (fig.5.1). They tend, however, to be slightly thicker than their basalt equivalents, with

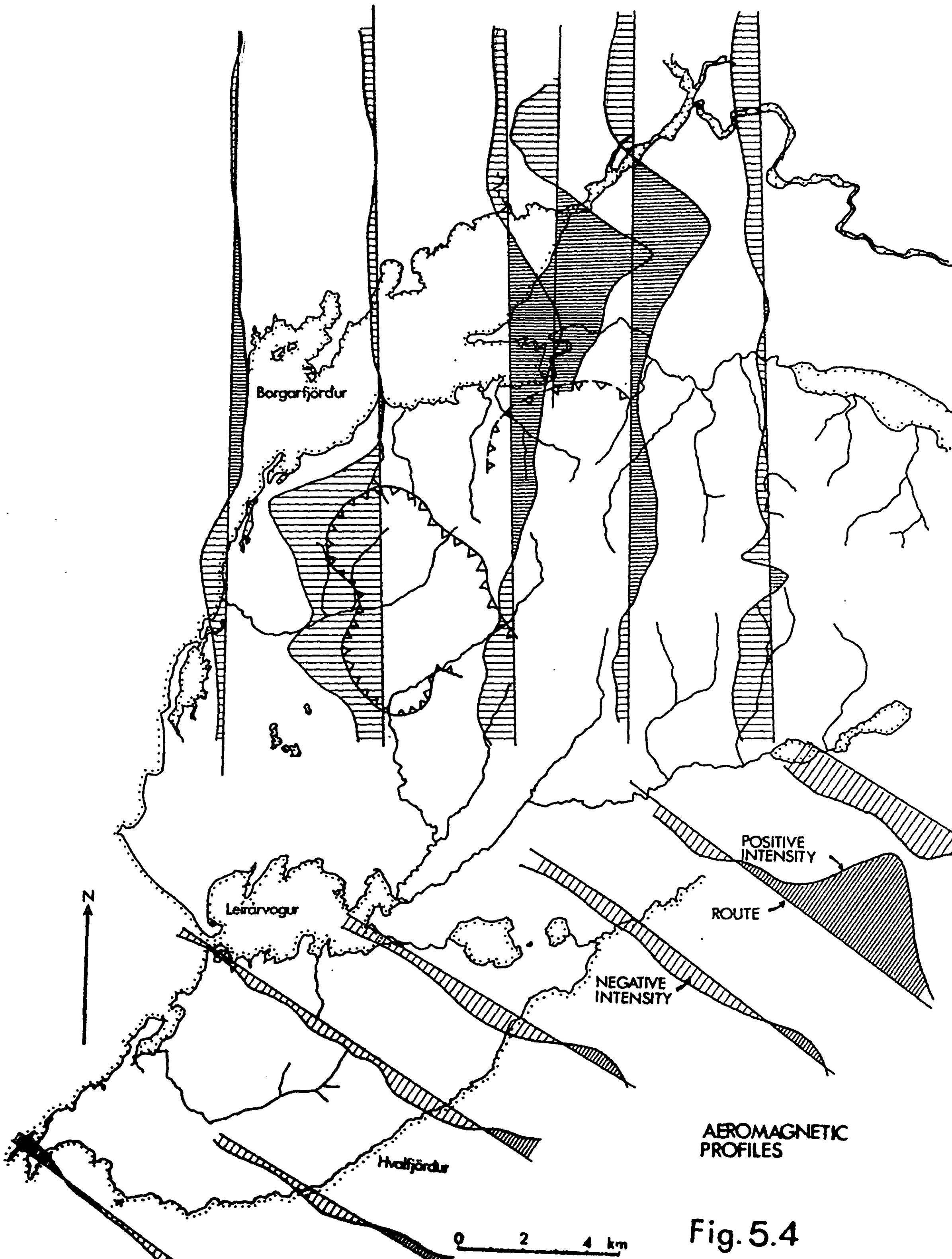

Borgarfjördur
Leirárvogur
Hvalfjördur
N
POSITIVE INTENSITY
ROUTE
NEGATIVE INTENSITY
AEROMAGNETIC PROFILES
0 2 4 km

Fig. 5.4

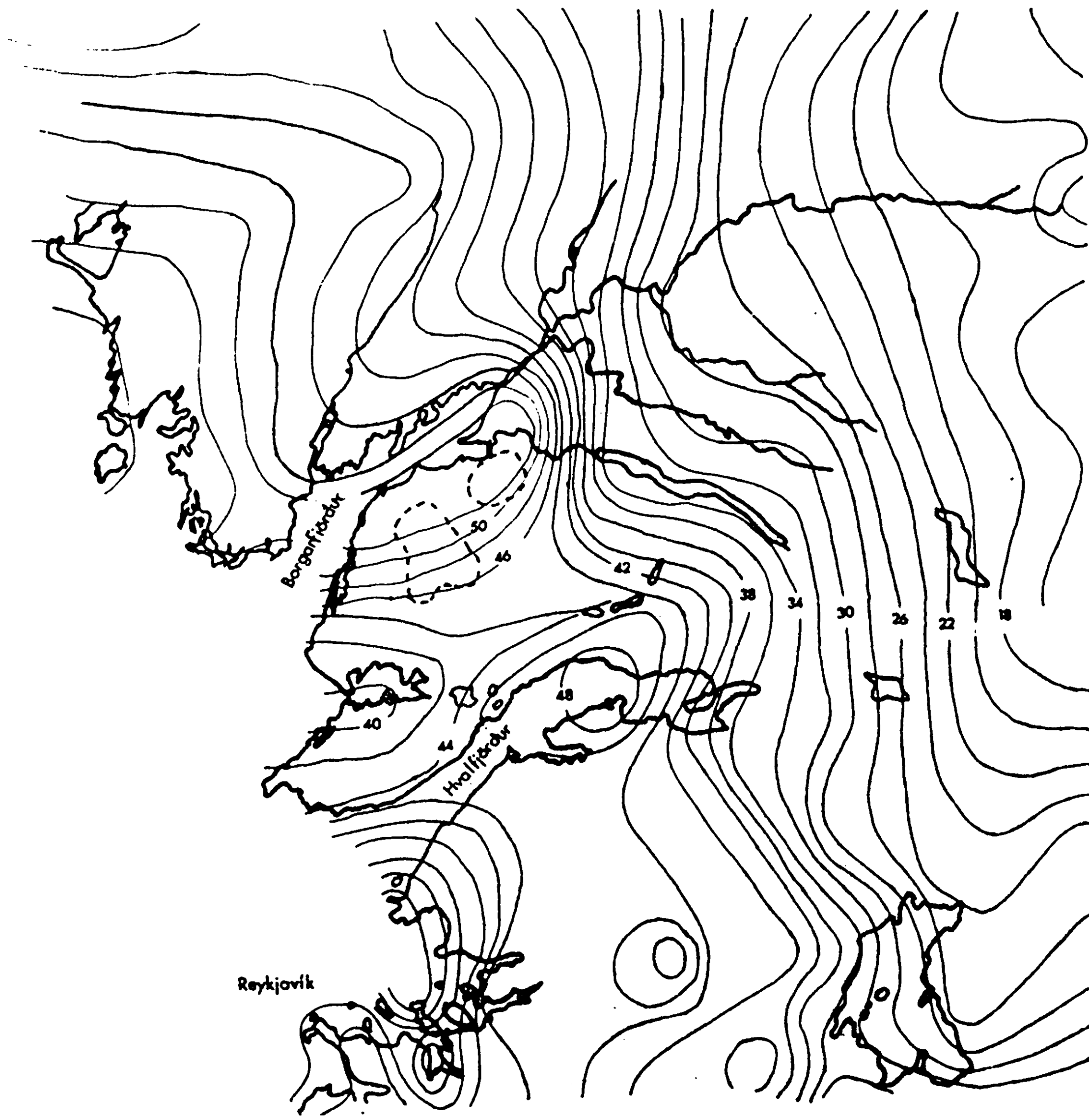


Fig.5.5

Unpublished preliminary gravity map of W-Iceland; isopachs in milligals. (With kind permission of Dr. Guðmundur Pálmason) a highest thickness frequency of c.2 m (fig.5.2,A).

b. Dykes of the flood-basalt succession.

To this group belong all dykes intruding the flood-basalt succession of the Hvalfjörður lenticular lava unit (fig.5.1 and 5.3). The dominant strike is N35°E but in eastern Skarðsheiði N55°E and N35°W trending dykes are also present. The NW dykes probably extend into the area intruded by dykes of the Skarðsheiði phase, but are not easily distinguishable from the latter.

These younger dykes represent the western edge of the swarm that fed the lenticular lava unit which culminates in the Hvalfjörður central volcano.

c. Dyke relationships.

The NE-NNE dykes, which are also an important component in upper-Borgarfjörður (Jóhannesson, 1975), reflect the approximate direction of the axial rift zone which was the precursor to the Reykjanes-Langjökull zone. The abrupt westward decrease in dyke intensity marks the western boundary of the dyke swarm, but the abrupt dyke disappearances are also likely to have been influenced by the boundary between the axial rift zone and the relatively rigid older crust (see chapter 6).

It is also interesting to note that when this swarm was being injected during the interval between the Brekkufjall and Hafnarfjall phases, similar lava types (i.e. porphyritic and olivine tholeiite basalts) were extruded both to the north and south of the central volcano (C1); such symmetrical behaviour was exceptional in the history of the area.

In relation to the NE-NNE approximate alignment of the axial rift zone, the strongly oblique ENE-WSW fissure swarm, predominating during the Hafnarfjall phase, is bound to have led to the creation of tensional stress field at each end of the fissure swarm, aligned perpendicular to the axial rift zone. The significant number of NNE to NE trending dykes in the Ölver and Snókur area (c.f. fig.5.3) may be an indication of such tensional stress field operating at the southwest termination of the Hafnarfjall phase fissure (dyke) swarm.

The well represented N-NNW dykes noted by Jóhannesson (1975) in the upper-Borgarfjörður region, may well be a continuation of those seen in the area (3). The abrupt increase in the thickness of the lava sequence and the concominant decrease in sediments in the Hvítársíða area (McDougall et al.,1977) coincide in time with the onset of Skarðsheiði phase. This suggests that, as in the Skarðsheiði area, the N-NNW trending dykes were the probable feeders of these lavas in the Hvítársíða area.

The dyke swarm shifted eastwards by c.15 km during the first three growth phases of the central volcano; the rate of rift implied is in accord with earlier estimates on spreading velocities in Iceland (e.g. Talwani et al.,1971). The fourth phase is anomalous in this respect as it indicates a temporary westward shift of the dyke swarm. These shifts were not gradual but abrupt, and it is interesting to note the close coincidence of the intermediate and acid rocks with the densest part of each dyke domain.

The ENE and NNW dykes may be treated as conjugate components related to a common NNE-NE axial rift direction. Thus, after the close of the rifting associated with the Hafnarfjall-Skarðsheiði lenticular lava unit, the net rifting occurred perpendicular to the direction of the axial rift zone.

The dykes penetrating the overlying flood basalt succession trend obliquely with respect to the strike of the basalt lavas and the isopachs of the basalt series.

5.2. Sheets

Those intrusives having relatively shallow inclinations ($< 60°$) are considered separately from the steeper (generally near-vertical) dykes and will be referred to simply as "sheets". The distribution of sheets in the area is shown in fig.5.6.

a. The Hvítá sheet-swarm

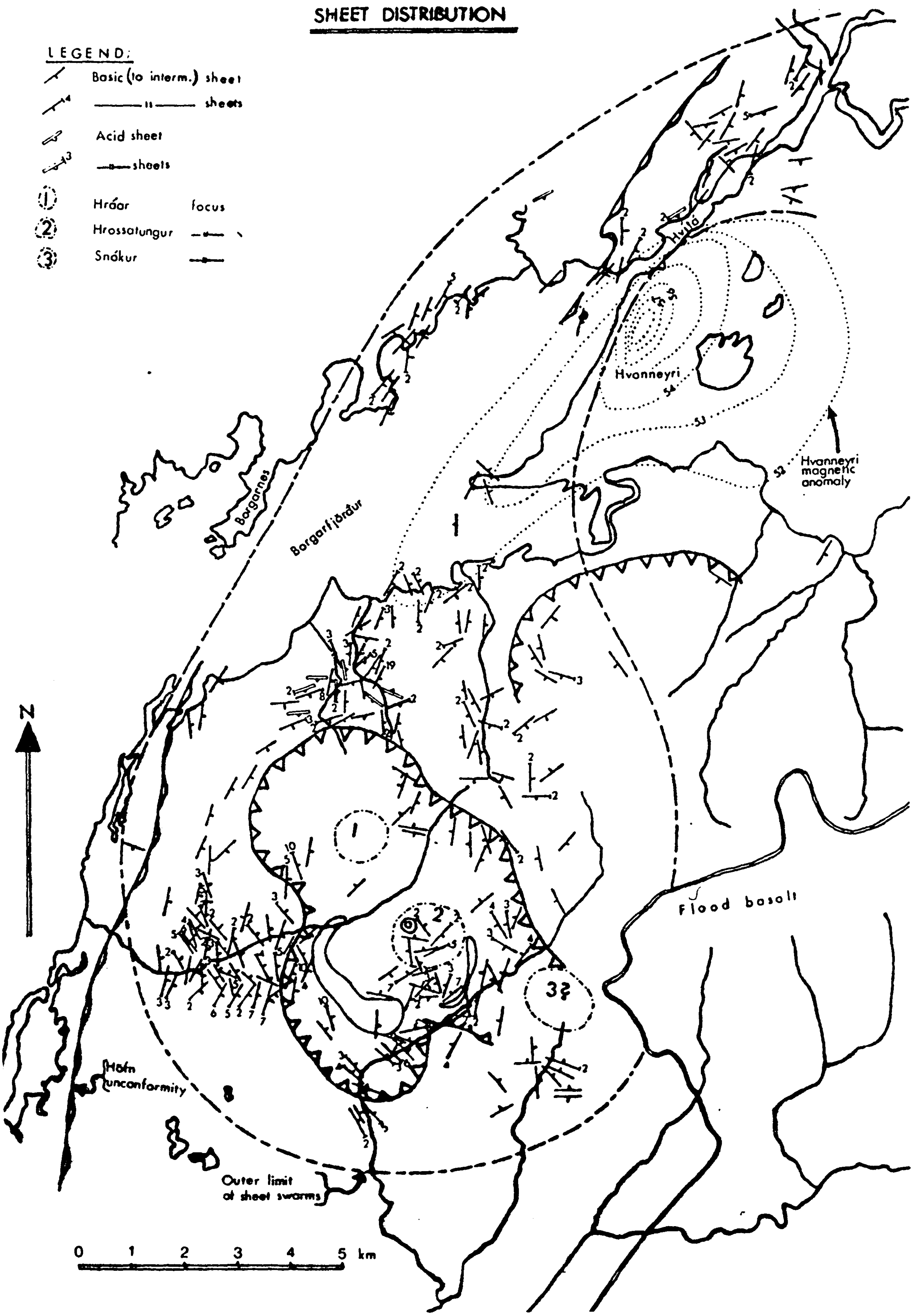
A reconnaissance survey of this sheet-swarm was carried out north of Borgarfjörður. The swarm forms a belt 3-4 km wide, running from the Hvítá-Grímsá intersection in the north southwards to the northern and northwestern parts of Hafnarfjall, where it merges with the Hafnarfjall sheet-swarm. The sheets generally strike NE-SW and dip 20°- 60° SE. Olivine tholeiite sheets predominate but a fair number of tholeiitic, intermediate and acidic sheets are present.

The sheets relate to the Hvanneyri magnetic anomaly in that they are generally aligned parallel to the magnetic contours (fig.5.6), and are predominantly normally magnetized. The absence of comparable sheet-swarms east of the magnetic anomaly is probably due to their concealment beneath younger formations. A few westerly dipping sheets in the northern part of Tungudalur may represent a small part of such a swarm. The relative proportions of different compositions in the swarm may reflect those of the deeper-seated intrusives responsible for the Hvanneyri anomaly.

b. The Hafnarfjall sheet-swarm

The Hafnarfjall sheet-swarm is concentrated around the caldera and was mainly intruded during the second volcanic phase. The sheets vary in thickness from 0.5 m to $>$ 8 m, with the highest frequency

Fig.5.6


SHEET DISTRIBUTION
LEGEND:
Basic (to interm.) sheet
sheets
Acid sheet
sheets
Hróar focus
Hrossatungur
Snókur
Hvítá
Hvanneyri
Hvanneyri magnetic anomaly
Borgarnes
Borgarfjördur
Flood basalt
Höfn unconformity
Outer limit of sheet swarms
0 1 2 3 4 5 km
N

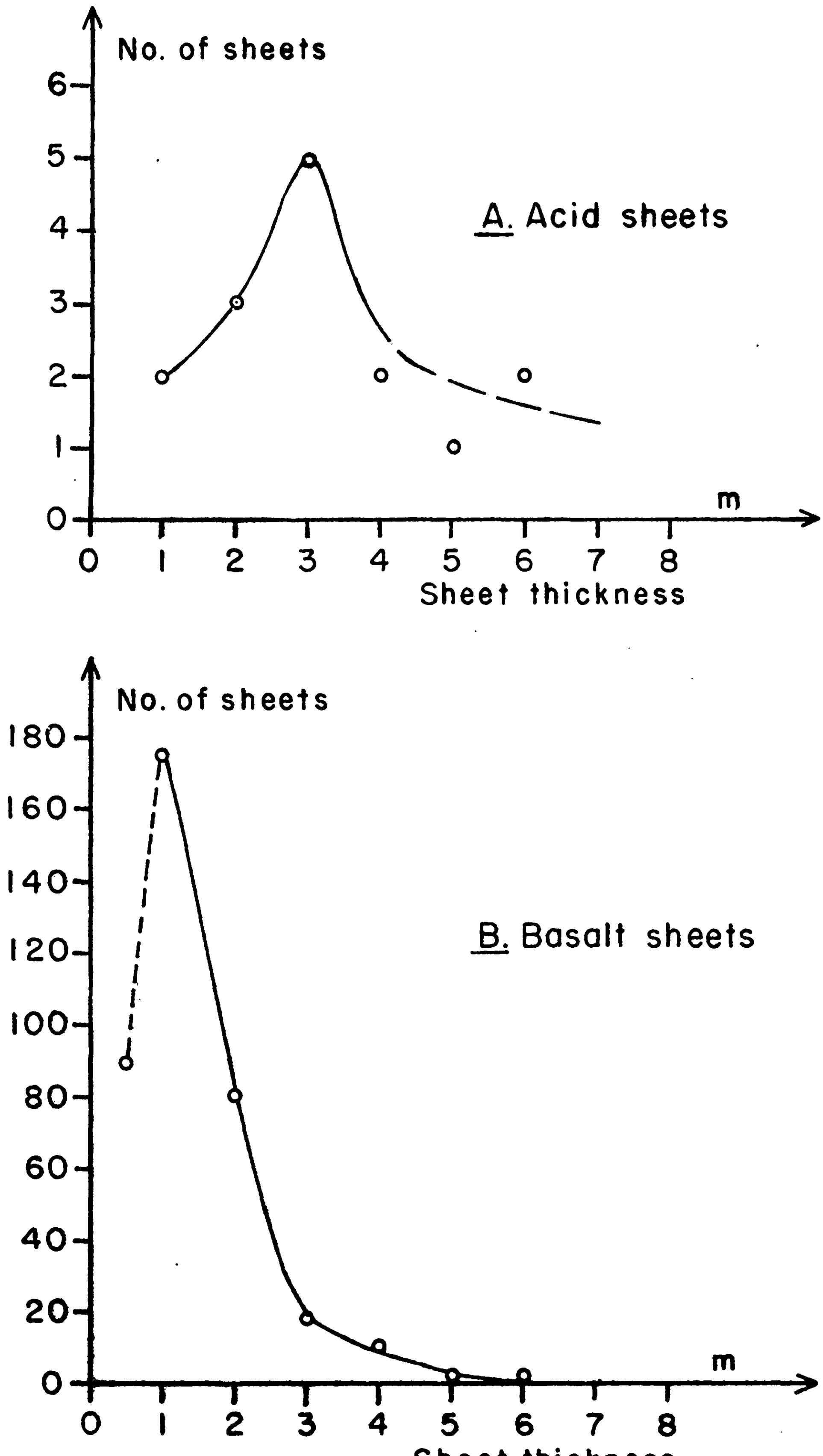


Fig. 5.7. Number and thickness of A. acid and B. basic sheets.

around 1 m (fig.5.7). The average thickness of 380 basalt sheets (Hvítá swarm included) is about 1.3 m. The sheets are mostly aphyric and basaltic, with a subordinate amount of more differentiated compositions (fig.5.7,A). The cone-sheets are divisible into two groups converging at two different focal levels:

(i) The shallow focus cone-sheets, whose dip suggests origin less than 1 km deep, are mainly found at two locations:

1) NW-Tungukollur, belt (approximately 1 km wide) of rhyolite cone-sheets encircles the top of the rhyolite intrusion. These sheets, which frequently show granophyric texture, increase in number towards the intrusion.

2) In the vicinity of the Hrossatungur gabbro where a number of basaltic sheets extend out from the gabbro. These are especially notable to the south and southwest of the gabbro where they give up 50% dilation of the basalt lavas. Most of the sheets are porphyritic, but the porphyritic aspect is progressively obscured in the thicker and more slowly cooled sheets, which may show gabbroic texture. This implies that the sheets were intruded during the cooling history of the main gabbro. The porphyritic sheets show in several instances flow differentiation, with porphyritic centres and nearly aphyric margins.

(ii) Deep-focus sheets, which constitute the bulk of the swarm converge towards a depth of 2-4 km. As in (i) above, the estimates of focal depth are based on the assumption, that the observed dip is maintained at depth since no variation in inclination with topographic height has been observed. The sheets dip at 20° - 60° (with a slight dominance in the 50° - 60° inclination interval). The swarm has an outer diameter of approximately 10 km and a slight N-S elongation. Most of the sheets can be related to one of three focal points, each of which coincides with the geometric centre of one of the basins involved in the caldera complex (chapter 3).

a) Hróar sheet swarm

The sheets in this group roughly converge to a focus below the centre of the Hróar basin (fig.5.6). A few southward dipping rhyolite sheets in northern Hafnarfjall and a number of gabbroic sheets west of Hróar belong to this group.

b) Hrossatungur sheet-swarm

The focal point of this swarm underlies the centre of Hrossatungur basin (fig.5.6). Cross-cutting relationships in the Ölver mountain suggest contemporaenity with the Hróar sheet swarm. The Hrossatungur gabbro and the thick multiple dolerite sheets in Leirárdalur partially encircle (about 200°) the focal point towards which this sheet swarm is directed, suggesting that these intrusions are also related to the swarm.

c) Snókur sheet swarm

The focal point of this swarm is not well defined but appears to lie below the Snókur basin (fig.5.6). Cross-cutting relationships with the other groups were not found, but judging from the age of the Snókur basin, the Snókur sheet-swarm is likely to have developed relatively late.

c. Sheet relationships

The intrusion of a cone-sheet swarm marks an evolutionary stage in many of the Icelandic central volcanoes (c.f. Sigurðsson, 1966; Annels, 1968; Friðleifsson, 1973; Jóhannesson, 1975). When the origin of the Hafnarfjall cone-sheet swarm is considered the following observations must be taken into account:

(i) The depth of focus of the Hafnarfjall swarm coincides approximately with the upper limit of crustal Layer 3 in the area (Pálmason, 1971).

(ii) A close affinity in time and space exists between the foci and the subsidence of the basinal structures of the caldera.

(iii) The axis joining the foci lies roughly at a right angle to the dominant dyke trend (ENE) of the second phase.

(iv) Predominantly the densely porphyritic sheets propagating from the Hrossatungur gabbro (a result of multiple magma injections into slowly crystallizing gabbro body) contrast with the bulk of the cone-sheets which are essentially aphyric.

(v) The spectrum of chemical compositions in the cone-sheets, (intruded in no discernible rational order) is very similar to that observed in the dykes and extrusives.

(vi) A sharp reduction in the concentration of dykes usually occurs within the cone-sheet swarm.

From these observations it would seem improbable that there ever existed large high level magma chamber (c.f. Anderson, 1937; Sigurðsson, 1966), from which the cone-sheets propagated and into which the caldera floor conveniently collapsed. It is more plausible to suggest that the cone-sheets and caldera subsidences are fundamentally attributable to an upper crustal (1.1 and 1.2) stress field, due to downsagging of the underlying anomalously thick crustal Layer 3 (see chapter 9).

Short-term lateral shifts in the areas of the maximum rifting within the fissure swarm domain has been noted in Krafla (Sæmundsson et al., 1975) and Torfajökull (Sæmundsson, 1972). Probably the three foci of the Hafnarfjall sheet-swarm reflect similar shifts occurring within the dominating ENE-dyke swarm of Hafnarfjall phase.

5.3 Major intrusions

Five large intrusions occur on surface within the central volcano, and indications of large intrusions at shallow depths are found at three other locations. The locations of the intrusions are shown in fig.5.10.

a. The Flyðrur granophyre

To judge from the extensive updoming of the overlying strata (fig.5.8,A) the Flyðrur granophyre which crops out through the upper scree slopes of western Hafnarfjall, represents the top of a large intrusion. The intrusion exhibits a multiple sheet structure as illustrated schematically in fig.5.9,A. It is suggested that this is the result of rapid spasmodic magma injections where each sheet intruded along the upper boundary of the previous one. The intrusion may be related to the acid sheet-swarm intruding the northern tip of Hafnarfjall. The granophyre, which is very fresh, has been dated at 3.9 $\pm$ 0.6 m.y. (Moorbath et al.,1968), which agrees reasonably well with the age of 4.0-4.3 m.y. inferred from other geologic data.

b. The Hafnardalur gabbro

This poorly exposed gabbro on the northern slopes of Ölver was probably intruded during the Hafnarfjall phase. It is believed to have an elongated outcrop and to have been intruded along a stratigraphic boundary.

c. The Hrossatungur gabbro

This gabbro intrudes incoherent and structureless pyroclastics within the Hafnarfjall caldera except in the south and west where the

Fig.5.8,A

Updoming above the Flyðrur granophyre (1) in western Hafnarfjall.

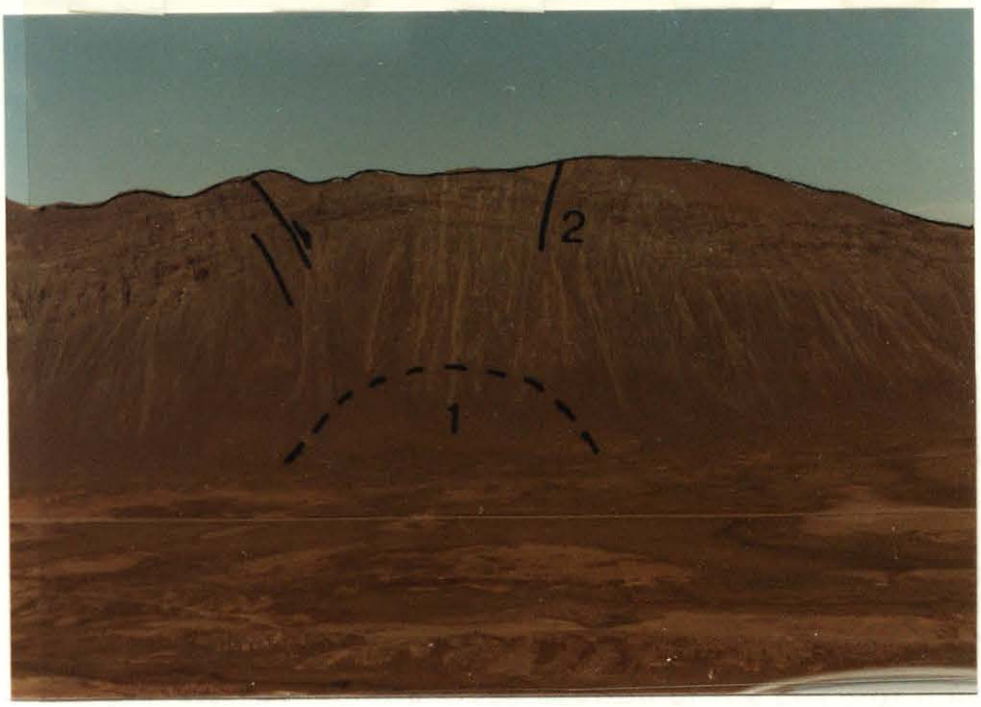


Fig.5.8,B

Updoming and fracturing above the inferred gabbro intrusion (1) south of Flyðrur granophyre.
2. Fracture.

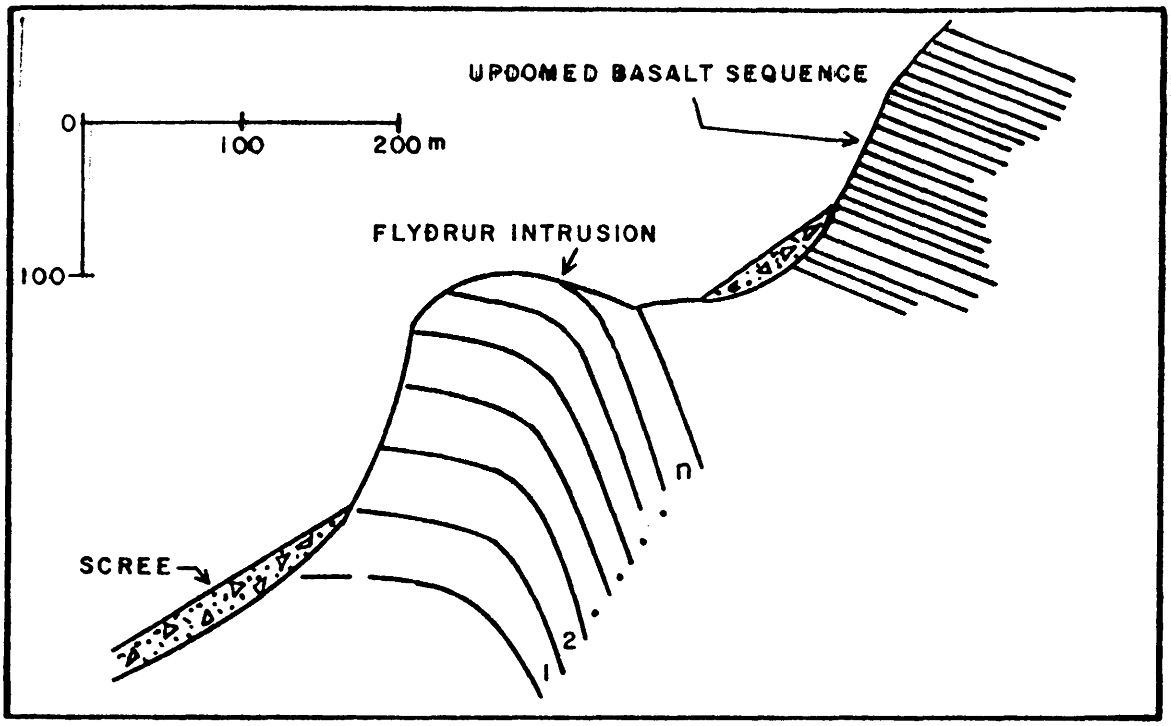


Fig. 5. 9, A. Schematic cross section of Flyðrur granophyre.
1 → n, probable intrusive sequence

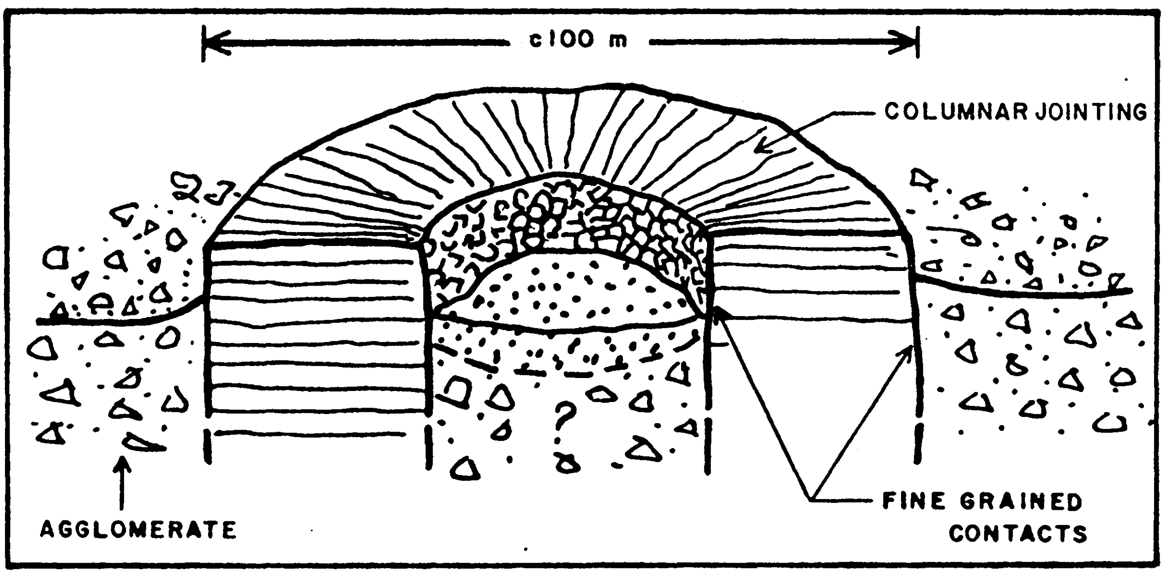


Fig. 5. 9. B. Schematic cross section of the circular dolerite plug in Hrossatungur

intrusion updomes the basalts underlying the pyroclastics.

The gabbro could be considered as a cone-sheet with a diameter of c. 3 km and a focus at a depth of 0.5-1.0 km b.s.l. The intrusion is thickest in the southwest (max. 200 m) but thins to a 10-20 m thick multiple dolerite sheet in Leirárdalur.

The following observations suggest that the gabbro body is the result of numerous, small-volume injections of magma inflating the country-rock envelope:

1) Chemical analyses indicate variable compositions from a slightly quartz normative tholeiite to basaltic andesite composition.

2) The associated cone-sheets (see b. above) indicate that magma injections occurred throughout the crystallization of the intrusion. At at least one location a late magma batch is observed to have intruded a crystallized forerunner.

The emplacement of the gabbro may be assumed to have occurred during the reverse-polarity interval between the Sidufjall and Nunivak events at 4.33-4.09 m.y. (McDougall et al.,1977), i.e. coincident with the Skarðsheiði extrusive phase. The reasons for this conclusion are threefold: (i) No Hafnarfjall cone-sheets cut the intrusion. (ii) The multiple dolerite sheet in Leirárdalur post-dates the normally-magnetized lava sequence in the Snókur basin. (iii) The near surface pulsatory emplacement of the intrusion at a depth of less than 200 m probably gave rise to a number of extrusions. The porphyritic lavas and pyroclastics occupying the top part of the sequence in the Snókur basin are regarded as probable remnants of such an extrusive episode.

The ring-like dolerite intrusion (fig.5.9,B) directly above the focal point of the gabbro is probably contemporaneous with the gabbro and may represent an eroded volcanic plug.

d. The Tungukollur granophyre

This intrusion occurs low down on the northeastern Tungukollur. The exposed part consists of fine-grained rhyolite, but converging cone-sheets (see 5.6) indicate a larger intrusive body at depth. The granophyre, which is densely intruded by components of both the Hafnarfjall and Hvítá sheet-swarms, is reversely magnetized and was probably emplaced early in the Gilbert Epoch.

e. Skarðsheiði gabbro

This elongated gabbro intrusion north of Skessuhorn intrudes the thick sediment horizon on the boundary of the Hafnarfjall and Skarðsheiði phases. It shows normal-polarity, and was probably intruded during the Nunivak event at 4.0-4.1 m.y. (Klitgaard et al., 1975), contemporaneously with the eruption of the Heiðarhorn phase volcanics.

f. Hidden major-intrusions

Shallow-level unexposed intrusions are inferred in three areas (fig.5.10) from; a) updoming of overlying strata, b) cone-sheets and c) geophysical anomalies.

The largest of these, the Hvanneyri intrusion, is a composite body involving an assemblage of NNE-SSW elongated intrusions, where the range and proportion of chemical compositions may be similar to that of the closely related Hvítá sheet-swarm. The areal extent may conveniently be estimated from the pronounced positive magnetic anomaly (fig.5.4), the intensity of which is proportional to the degree of updoming in the overlying basalt succession. The intrusions

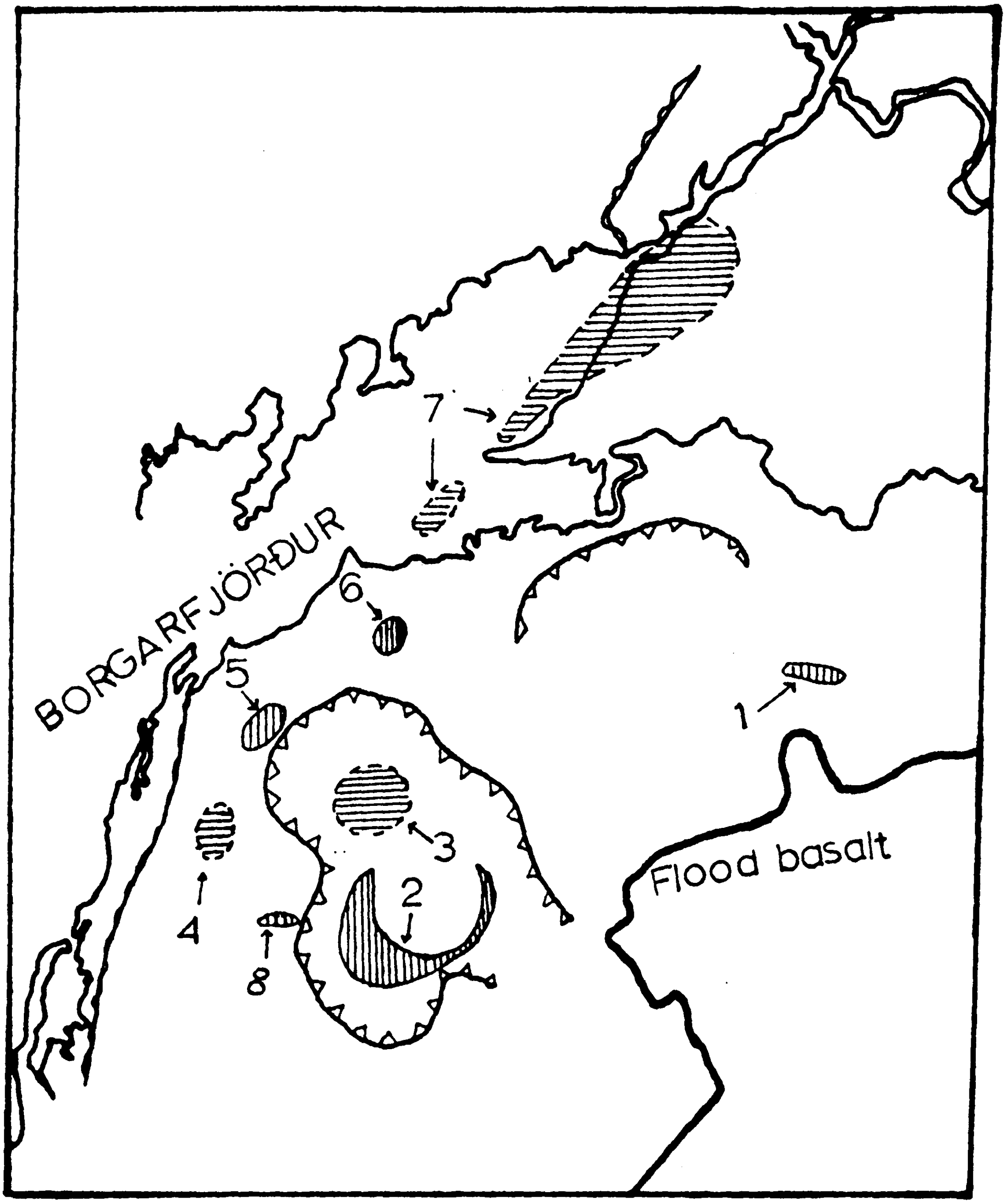


Fig.5.10 Approximate location of major intrusions. Vertical lines = exposed, Horizontal lines = inferred intrusions. 1. Skessuhorn gabbro 2. Hrossatungur gabbro 3. Hróar gabbro 4. Inferred gabbro, west Hafnarfjall 5. Flyðrur granophyre 6. Tungukollur granophyre 7. Hvanneyri intrusions.

are further characterized by high gravity values as shown in fig.5.5. They are likely to have been trapped by a zone of densely faulted and fractured country rock underlying the Höfn unconformity. The strong magnetic anomaly indicates an intense intrusive episode during a single normal-polarity interval, most probably towards the end of Epoch 5. This is supported by the apparent absence of any components of the Hvítá sheet-swarm in younger rocks. The voluminous outpourings of intermediate and acid rocks and concominant caldera formation during the Brekkufjall acid phase probably represent the culmination of this intrusive episode.

The Hvanneyri magnetic anomaly was first recorded by Sigurgeirsson (1970), who pointed out that it lay, along with three other anomalies, on a single straight line at an angle of about 45° with the fissures of the Reykjanes-Langjökull rift zone. These anomalies are regularly spaced along this line. Comprehensive studies of one of these anomalies, which underlies with the Stardalur caldera (Steinþórsson and Sigvaldason 1971, Friðleifsson and Kristjánsson 1972, Friðleifsson 1973), have confirmed, the cause of this to have been by a high geomagnetic field strength at the time of formation as well as an unusually high partial pressure of oxygen of the erupted magmas. Friðleifsson went on to suggest that all the four anomalies may have developed in a similar way as a consequence of a melting spot, characterized by high partial pressure of oxygen within the main spreading zone, and which is migrating southwards as a result of asthenopheric flow away from the hypothesized Icelandic "hot spot".

The second inferred intrusion is in western Hafnarfjall, south of Flyðrur granophyre. Its presence is suggested by the updoming of the lavas in a manner reminiscent of that seen around the Flyðrur intrusion (fig.5.9) and the gabbro boulders in the surrounding scree slopes may be derived from this intrusive.

The third (Hróar) intrusion, is thought to underlie the caldera filling in the Hróar basin. This is inferred from the presence of the shallow-focus gabbroic sheets referred to earlier (5.2). A high negative magnetic anomaly in the area (fig.5.4) may be regarded as further evidence supporting the postulation of such an intrusion.

g. Distribution of intrusions and intrusive mechanisms

While differential erosion of the southeasterly dipping volcanic succession has resulted in a higher proportion of intrusives being exposed towards the west of the research area, a conspicuously high proportion of the larger intrusive bodies is evident along a zone coinciding with the Höfn unconformity, the basalt flexure zone and the western limit of the dyke swarm (fig.5.10). This zone, to be dealt with in more detail in chapter 6, marks the boundary between two crustal segments formed within different rift zones, the Breiðafjörður rift zone to the northwest, and the Reykjanes-Langjökull rift zone on the east side.

In contrast, the area south of Hafnarfjall is characterized by low gravity values and smooth aeromagnetic patterns (figs.5.4 and 5.5) indicating an absence of larger intrusions. This also accords with the very low dyke dilation (fig.5.1) and extrusion rate in the area.

The emplacement mechanism of larger intrusions in Iceland has been discussed by Friðleifsson (1976) and Walker (1974,1975), who proposed that the probability of emplacement is likely to depend on; (a) the structure and density of the host rock and (b) such properties of the magma batches involved as frequency of uprise, total volume, rate of delivery and density.

In the research area it is clear that the ready yielding of unconsolidated and structurally isotropic host rocks has facilitated intrusion as is clearly seen in the case of the Hrossatungur and Skarðsheiði gabbro intrusions. The structure of such intrusions as the Hrossatungur gabbro, Flyðrur granophyre and (somewhat more doubtfully) the Tungukollur granophyre suggests the importance of an intrusive mechanism involving repeated rapid injection of small volumes of magma.

CHAPTER 6

TECTONIC EVOLUTION

6.1 Faults

Faulting in the area west of the Höfn unconformity is not included in this study, due both to the scarcity of outcrops and insufficient mapping.

Normal faulting (c.f. geological map) in the research area is divisible into two groups on the basis of age.

a. Faults contemporaneous with the Hafnarfjall-Skarðsheiði lenticular lava unit

Lack of exposure in the low ground, coupled with inundation of much of the region by the overlying lenticular lava unit makes evaluation of faults difficult, and thus gives a distorted picture of their distribution.

NE-SW faults dominate with rare occurrences of N-S and ENE-WSW faults. The throw of these faults, which almost invariably downthrow to the west, is generally less than 50 m, with the exception of the Hvítá river fault (see chapter 2) which has a throw of 150-200 m. (The fault(s) associated with the Skálafjall-Grjóteyri flexure is discussed separately (6.3)). An unequal distribution of faults across the Ölver-Hvítá flexure, is well illustrated by the contrast between frequent faulting of the strata in Brekkufjall area and the relatively unfaulted zone extending from the western end of Hafnardalur to Höfn unconformity. This feature, as more fully discussed in 6.4, is believed to be due to the unequal response of two (tectonically) distinct crustal segments on either side of the flexure.

b. Faults contemporaneous with the Hvalfjörður lenticular unit

These faults strike predominantly NNE to NE and represent the western edge of a fault swarm associated with the Hvalfjörður lenticular lava unit. The throw of these faults is again generally < 50 m except for one fault north of Innrihólmur farm in S-Akranes, which forms the eastern boundary of a graben (throw c. 90 m). In Skarðsheiði the downthrow is predominantly easterly, and the faults are therefore easily distinguishable from the earlier faults. These faults, like the dykes, trend obliquely with respect to the strike of the lavas. The frequency of faulting, however, appears to increase southeastwards as the lava sequence thickens. This is observed in Skarðsheiði, where faulting is rare to the north and west, but becomes frequent in eastern Skarðsheiði (Haraldsson, 1975) and in Miðfellsmúli to the south (Ólafsson, 1976). Akrafjall and Miðfellsmúli occupy a similar position within the fault zone and the fault frequency may consequently be expected to fall off rapidly on the lowlands west of Akrafjall and north of Leirárvogur. This prediction of fault distribution may be important as it decreases the probability that the waters for the hot-spring area at Leirá farm ascend along fault planes of this group.

6.2 The Ölver-Hvítá flexure

This flexure is defined as the zone along which the subhorizontal succession above the Höfn unconformity is flexed southeastwards towards the Reykjanes Langjökull rift zone.

The flexure is well displayed along the southern slope of Ölver (fig.6.1) but its northward continuation is partially obscured

Fig.6.1

The Ölver-Hvítá flexure in the southern
face of Ölver mountain
1. Lava horizon

by the superimposition of the Hafnarfjall caldera and the updoming by the intrusions in the Hafnarfjall and Hvítá areas. North of Hvítá it is evidenced by the gradual increase in inclination from a few degrees above the unconformity to more than 20° across a distance of c. 2 km.

Constant lava thicknesses across the flexure (as shown by the Hafnarfjall Olivine Tholeiite Series) demonstrate that the flexure is not due to variation in the deposition slopes. It is likely that the flexure was formed as a result of prolonged extrusive and intrusive magmatism in the area and it is believed to express the greater rate of subsidence of the more ductile crust of the (contemporaneously active) axial rift zone on the one hand relative to that of the older and more rigid crust underlying the Höfn unconformity on the other (fig.6.2).

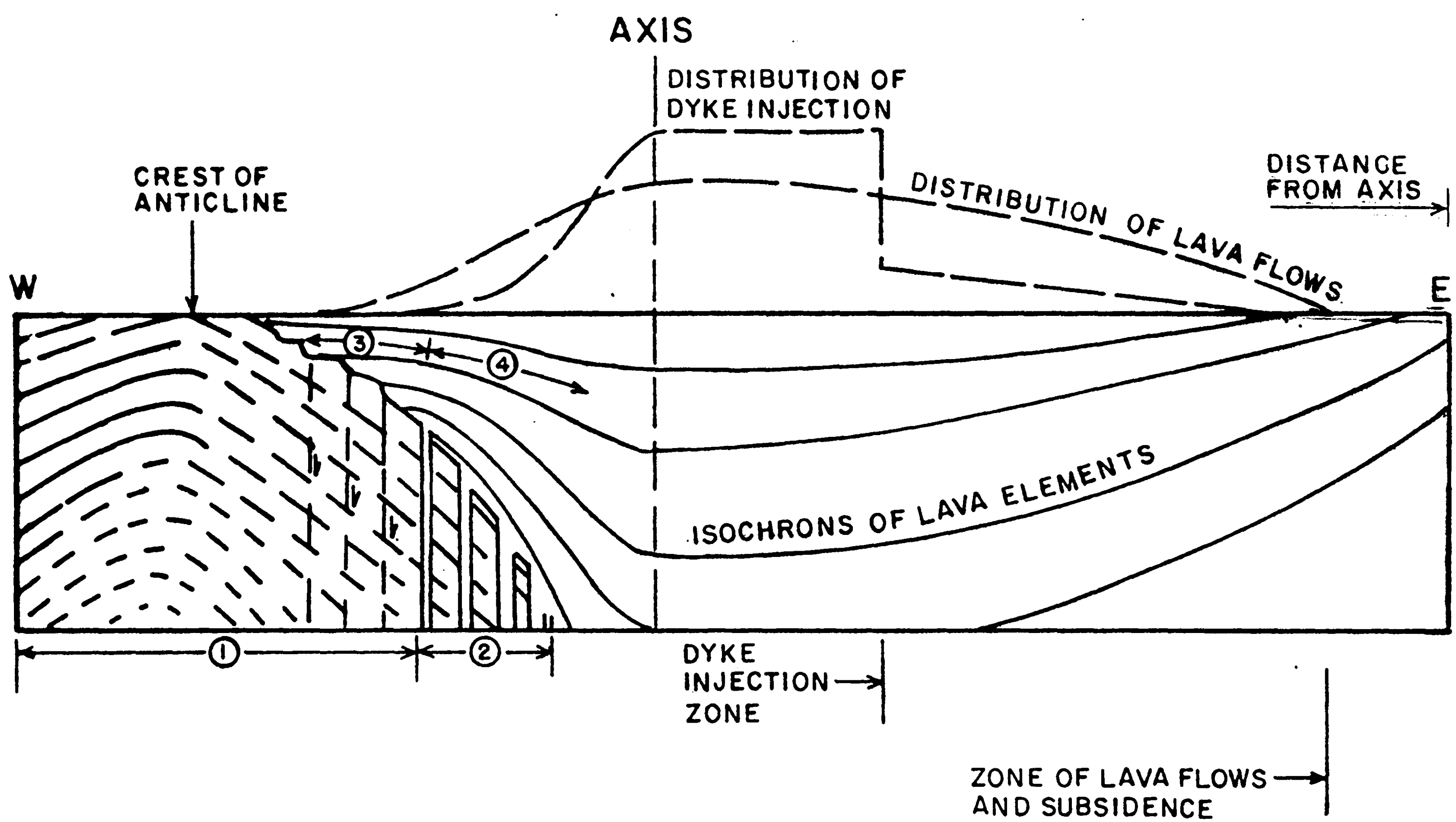
6.3 The Skálafjall-Grjóteyri "flexure"

A NNW-SSE trending zone of steeply dipping basalts (40°-50°E) outcrops from Grjóteyri (< 200 m wide) south along the western edge of Skálafjall (c. 500 m wide) until it disappears southwards beneath the Brekkufjall and the Hafnarfjall Tholeiite Series (fig.6.3). These (largely tholeiitic) lavas with thicknesses of 1-3 m are locally interbedded with breccias. The Skálafjall-Grjóteyri flexure which in this area cuts across the Ölver-Hvítá flexure, represents the western margin of a graben with an overall subsidence of 500-800 m, which developed gradually throughout most of the Brekkufjall phase.

The schematic model illustrated in fig.6.4 explains its probable northward disappearance as the level of erosion progressively

Fig.6.2

A schematic cross-section of the boundary between the older crust and the active spreading axis. The right side of the diagram is taken from Pálmason (1973).



(1) A RELATIVELY RIGID OLD BASEMENT

(2) A RAPID EASTWARD INCREASE IN DYKE DILATION. A TRANSITION ZONE OVER TO DUCTILE CRUST OF THE AXIAL RIFT ZONE.

(3) SUBHORIZONTAL BASALT SEQUENCE

(4) FLEXURE

Fig. 6.2

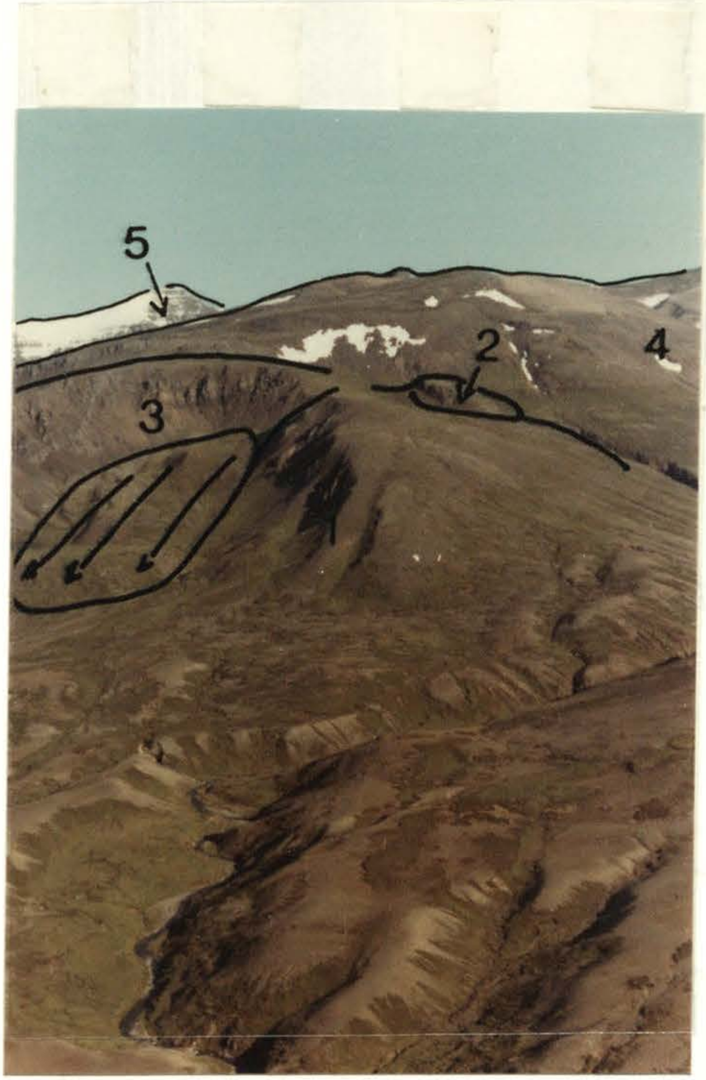


Fig.6.3

A view towards south along the Skálafjall -Grjóteyri flexure .
1. Skálafjall-Grjóteyri flexure 2. A composite vent 3. The western end of the Brekkufjall Caldera Series 4. Rauðhnúkafjall 5. Heiðarhorn.

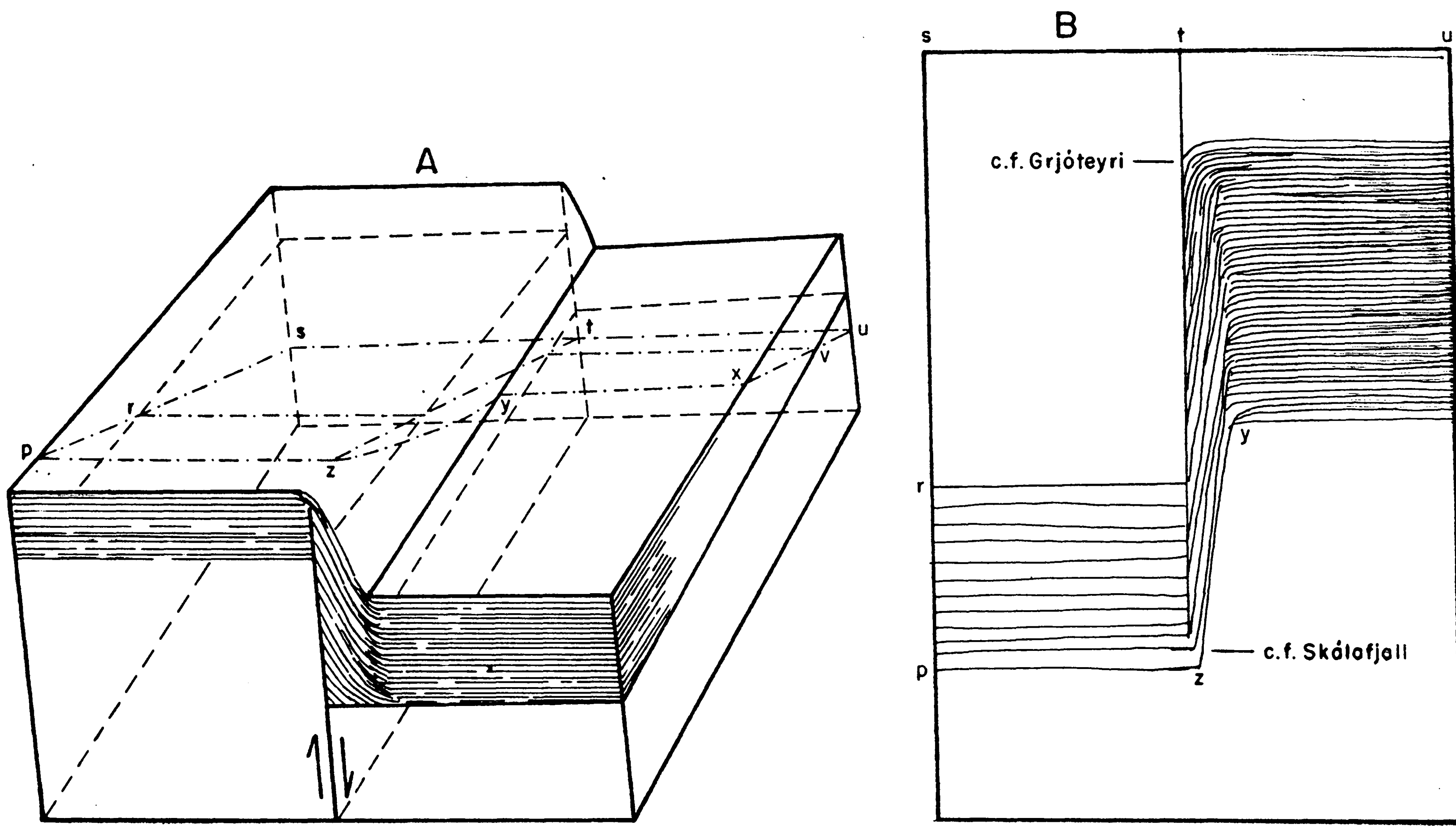


Fig. 6.4

deepens below the level at which the flexure is expressed. A number of N-S to NNE-SSW trending faults in the basalt succession below the Höfn unconformity north of the Hvítá, may possible represent the northerly extension of this flexure, but verification of this would require further field work.

6.4 Tectonic Environment

A brief outline of the model of Aronson and Sæmundsson (1974) is given in chapter 2; this model proposed that the crest of the Borgarnes anticline demarcates the boundary of the domains of two axial rift zones. In the upper Borgarfjörður lowlands, Jóhannesson (1975) was able to show that the younger of these axial rift zones (the equivalent of the active Reykjavík-Langjökull zone) probably commenced with a formation of a graben structure, followed by sedimentation and extrusion of hyaloclastites, pillow lavas and thick basalt flows (the Hreðavatn Series). He also indicated that the tectonic styles,before and after this rift initiation, were different.

Although it would seem that a similar initial opening of the rift zone occurred in the research area, as appears likely, evidence of comparable early stages has been obliterated by the superimposition of the Hafnarfjall-Skarðsheiði central volcano, at the western margin of the rift.

However, the excessive loading of the central volcanic pile at the margin of the new rift zone, convincingly brings out the different physical properties of the two crustal segments as schematically shown in fig.6.5 and as summarised below:

1) The Höfn unconformity suggests that the anticlinal and synclinal tectonic disturbance within the old crust occurred largely

Fig.6.5

The crustal boundary in the research area as indicated by basalt flexuring, larger intrusives, sheet swarm and disappearance of dyke trends.

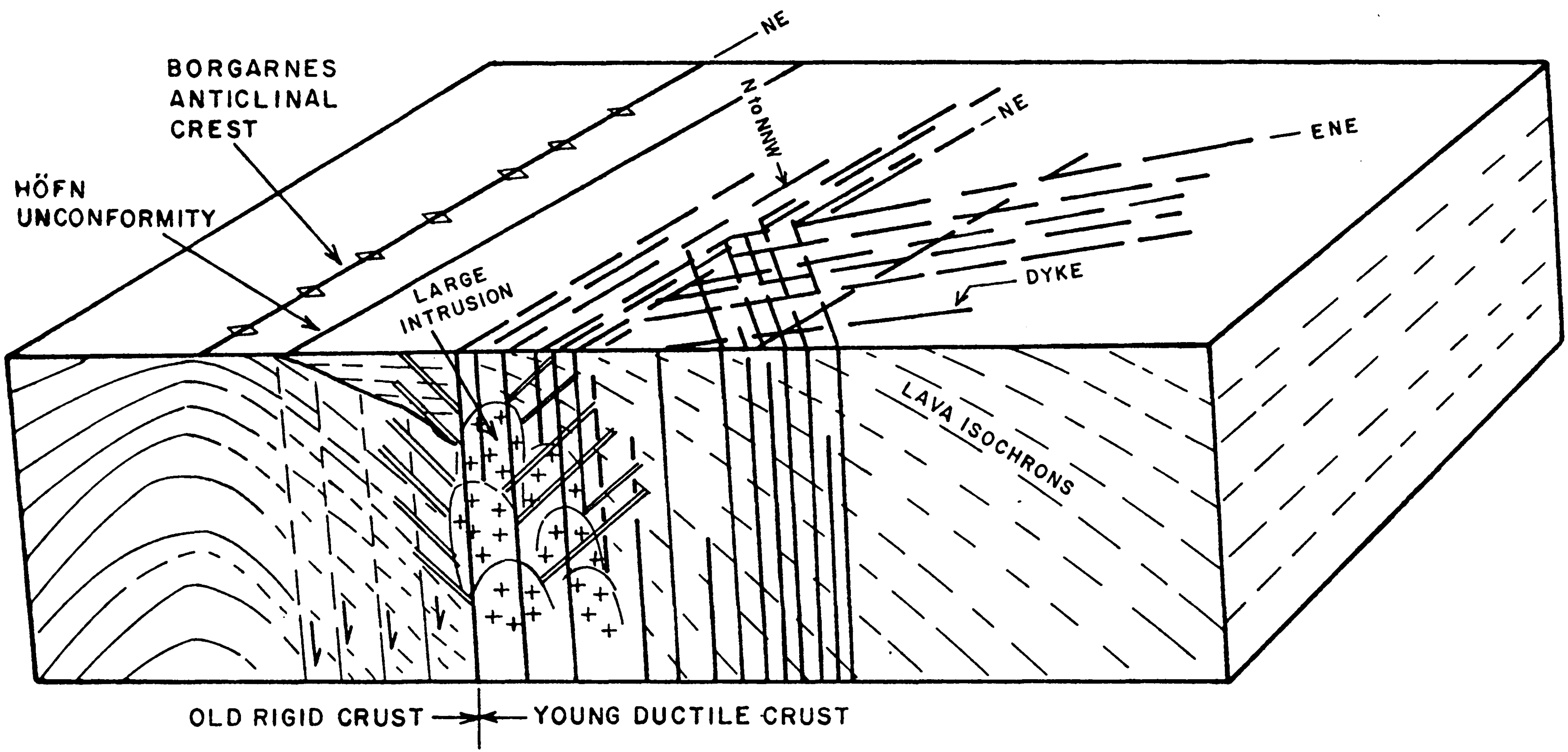

NE
BORGARNES
ANTICLINAL
CREST
N to NNW
NE
ENE
HÖFN
UNCONFORMITY
LARGE
INTRUSION
DYKE
LAVA ISOCHRONS
OLD RIGID CRUST
YOUNG DUCTILE CRUST

Fig. 6.5

prior to the accumulation of the Hafnarfjall Olivine Tholeiite Series; this possibly indicates that the rift zone was initiated with a formation of a graben structure.

2) The sub-horizontal basalt succession above the Höfn unconformity on the lowlands west and north of Hafnarfjall, rest on the relatively rigid old crust. This is also born out by the relatively infrequent faulting in that area. Thus the Ölver-Hvítá flexure represents therefore, the eastward transition towards a ductile crust of an axial rift zone (c.f. Pálmason, 1973). The apparent absence of 1) and 2) in the upper-Borgarfjörður lowlands may indicate a wider transitional boundary between the two crustal segments.

3) The abrupt disappearance of dykes west of the flexure (specially notable in dyke directions oblique to the NNE to NE direction of the rift zone) is an indication of the resistance of the older crust to tensional rifting.

4) Some of the larger intrusions, described in chapter 5 (fig.5.10) show a preferred alignment along the (inferred) crustal boundary. The possible causes of this are considered in chapter 9.

In view of the scarcity of data the cause of the pronounced differences in extrusive and intrusive rock abundancies found between the Hafnarfjall region and the Akranes lowlands is difficult to assess. However, the apparent scarcity of sediment within the succession, which according to McDougall et al.(1977) accumulates within a "normal axial rift zone at a similar rate (but inversely proportional) to that of the lavas", may suggest that the Akranes lowlands were decoupled from axial rifting conditions for long time intervals. If that is the case, it is plausible that WNW-to

NW-striking right lateral transform fault(s) may have been active north of Leirárvogur to relieve the crustal strain, induced by the differential rifting in Akranes and Hafnarfjall areas. Detailed tectonic mapping on the southwest shores of the Mýrar district to the west of Borgarfjörður can perhaps provide a solution to the problems outlined above. It appears logical to assume that fissure swarms develop at locations of greatest structural weakness within axial rift-zones. Furthermore, the width of an axial rift-zone(s) may also be an important factor in determining the number of structurally weak locations allowing fissure swarms to develop across its width. Thus, more than one active fissure swarm may develop within each section of a relatively broad axial rift-zone. The eastern volcanic zone north of Vatnajökull is a possible example of a broad axial rift-zone, where up to 6 separate fissure swarms occupy the rift zone (fig.1, in Sæmundsson, 1974). In contrast, rifting along a relatively narrow axial rift-zone is likely to be contained within a single fissure swarm.

The geological history of the research area suggests that, during the time involved in the accumulation of the Hafnarfjall-Skarðsheiði central volcano, the axial rift-zone evolved from an initial stage which involved the breaking of the older crust, to a relatively mature stage where new crustal addition by dyke dilation amounted to 30-40 km (assuming a rifting rate of 2 cm/yr). The life expectancy of axial rift-zone central volcanoes is generally between 0.5-1.0 m.y. (Piper, 1971; Sæmundsson and Noll, 1974). Thus it would be tempting to suggest that the fundamental reason for the unusually long life (1.5 m.y.) of the Hafnarfjall-Skarðsheiði central volcano is the narrowness of the rift-zone, which restricted fissure-swarm migration. This is even more plausible when considered in the light of the highly variable stress fields (c.f. dyke trends) operative during this time interval.

CHAPTER 7

ALTERATION AND EROSION

Secondary mineralization, generally represented by amygdale formation, has been used as an indicator of (i) the alteration state, (ii) the paleo-temperature gradient and (iii) the maximum depth of burial (Walker, 1960; Ade-Hall et al.,1971).

Over 20 amygdale minerals were identified in hand specimen in addition to which the identification of garronite, phillipsite and the discrimation between scolecite and mesolite, was confirmed by XRD. A distinction between two areas has been made on the basis of degree of alteration:

7.1 The Hafnarfjall-Skarðsheiði central volcano

The dominating amygdale assemblage within the central volcano consists of quartz, chalcedony, platy calcite and aragonite. The restricted range of the zeolites (rare occurrences of scolecite, mesolite, heulandite, stilbite and laumontite) is attributed chiefly to the predominantly tholeiitic to acid compositions of the country rock and to relatively high alteration temperatures. Propylitization is confined to areas adjacent to the major intrusions viz. the Hrossatungur gabbro, the Hvanneyri intrusion (c.f. the magnetic anomaly in fig.5.6) and also along much of the Hafnarfjall caldera margin. In these areas the rocks show extensive development of chlorite, pyrite and epidote. This relatively high-grade alteration is attributed to prolonged passage of convecting hydrothermal fluids associated with the slowly cooling intrusive bodies below which were also preferentially channelled along the fault planes of the caldera margin.

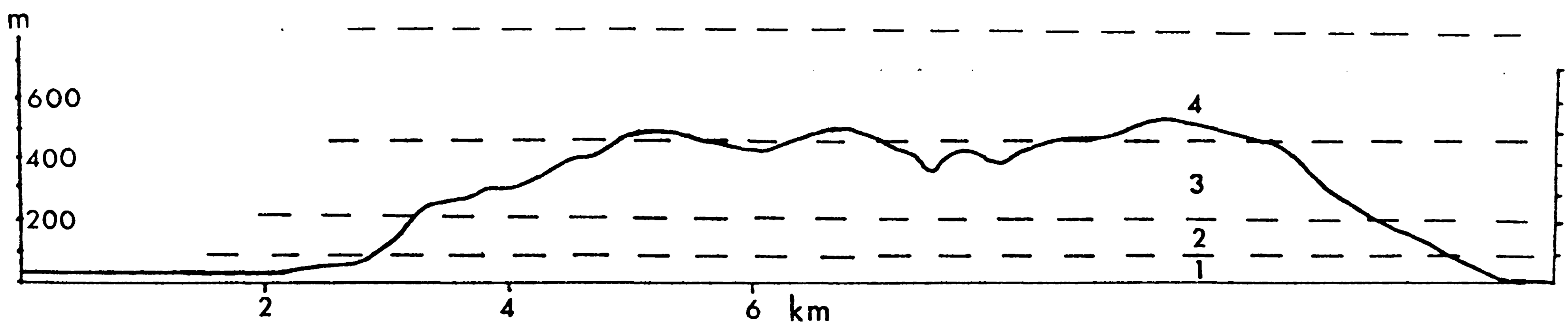
The high-grade alteration in the central volcano core represents a former "high temperature area" as defined by Árnason et al. (1969) i.e. an area where sub-surface temperatures in excess of 200°C are encountered at less than 1 km depth.

The appearance of the scolecite (mesolite), stilbite, heulandite assemblage in the basalt succession below the Höfn unconformity west of Hafnarfjall indicates a lowering of the alteration state to the scolecite-mesolite zone. Although more sampling is needed for verification, this complies with the sharply reduced dyke dilation there (c.f. fig.5.1), and may also represent the palaeotemperatures due to burial in the parental axial rift-zone in Breiðafjörður syncline.

7.2 Akranes-Skarðsheiði

A wide variety of zeolites are found in the Hvalfjörður lenticular basalt succession in Akranes and Skarðsheiði overlying the high temperature area of the central volcano.

The E-W cross-section of the Akranes peninsula in fig.7.1, shows the characteristic amygdale assemblages. These show a zonal distribution similar to that of the olivine basalts in Reyðarfjörður in E-Iceland (Walker, 1960). Thus the mesolite-scolecite zone coincides approximately with sea level, and the top of the chabazite-thompsonite zone lies close to the top of Akrafjall (700 m). In western Skarðsheiði there is an overall elevation of the zonal distribution of c. 300 m where the top of the chabacite-thompsonite zone occurs at approximately 1000 m a.s.l. This zeolite zone elevation may be attributed to the distances separating the two areas from the Hvalfjörður central volcano.



<u>Fig.7.1</u> An E-W cross section of Akranes, from Blautós in the west to Hvalfjörður in the east, showing approximately the zonal pattern of the amygdale assemblage. <u>1</u>. Scolecite-mesolite zone (scolecite, mesolite, stilbite, chabazite, thomsonite, opal, aragonite, analcime, calcite). <u>2</u>. Analcime zone (analcime, chabazite, thomsonite). <u>3</u>. Chabazite-thomsonite zone (chabazite, thomsonite, levyn). <u>4</u>. Amygdale-free zone.

It is thus estimated, that the original top of the volcanic succession lay 300-400 m above the top of the Akrafjall and W-Skarðs-heiði mountains.

CHAPTER 8

PETROLOGY

8.1 Introduction

The rather confusing rock nomenclature of Icelandic rocks up into the 1960's is likely to be attributable to the limited geological and petrological data available at that time and may also reflect the tendency of petrologists of different schools to adapt these to "local" petrological nomenclature systems.

Carmichael (1964) established a nomenclature for Icelandic rocks based on comprehensive mineralogical and geochemical data from Þingmúli central volcano. This nomenclature has been adopted by later workers dealing with volcanoes of Þingmúli type with only minor variations.

The chemical evolution of the Hafnarfjall-Skarðsheiði central volcano is very similar to that of Þingmúli as exemplified on the total alkalis versus silica plot (fig.8.1). The same nomenclature system is therefore used for the differentiated rocks of this study, and is analogous to that used by Jóhannesson (1975) except that basaltic andesite is substituted for basaltic icelandite on the grounds of slight linguistical superority (table 8.2).

The basaltic andesites, as will be discussed later in more detail, is further divided into the low-and high-Al groups.

Jakobsson (1972) and Jóhannesson (1975) used the Hawaiian division line (c.f. McDonald and Katsura, 1964) to distinguish alkali olivine basalts from tholeiites. The tholeiitic nature of the analysed basalt samples of this study is brought out in fig.8.4.

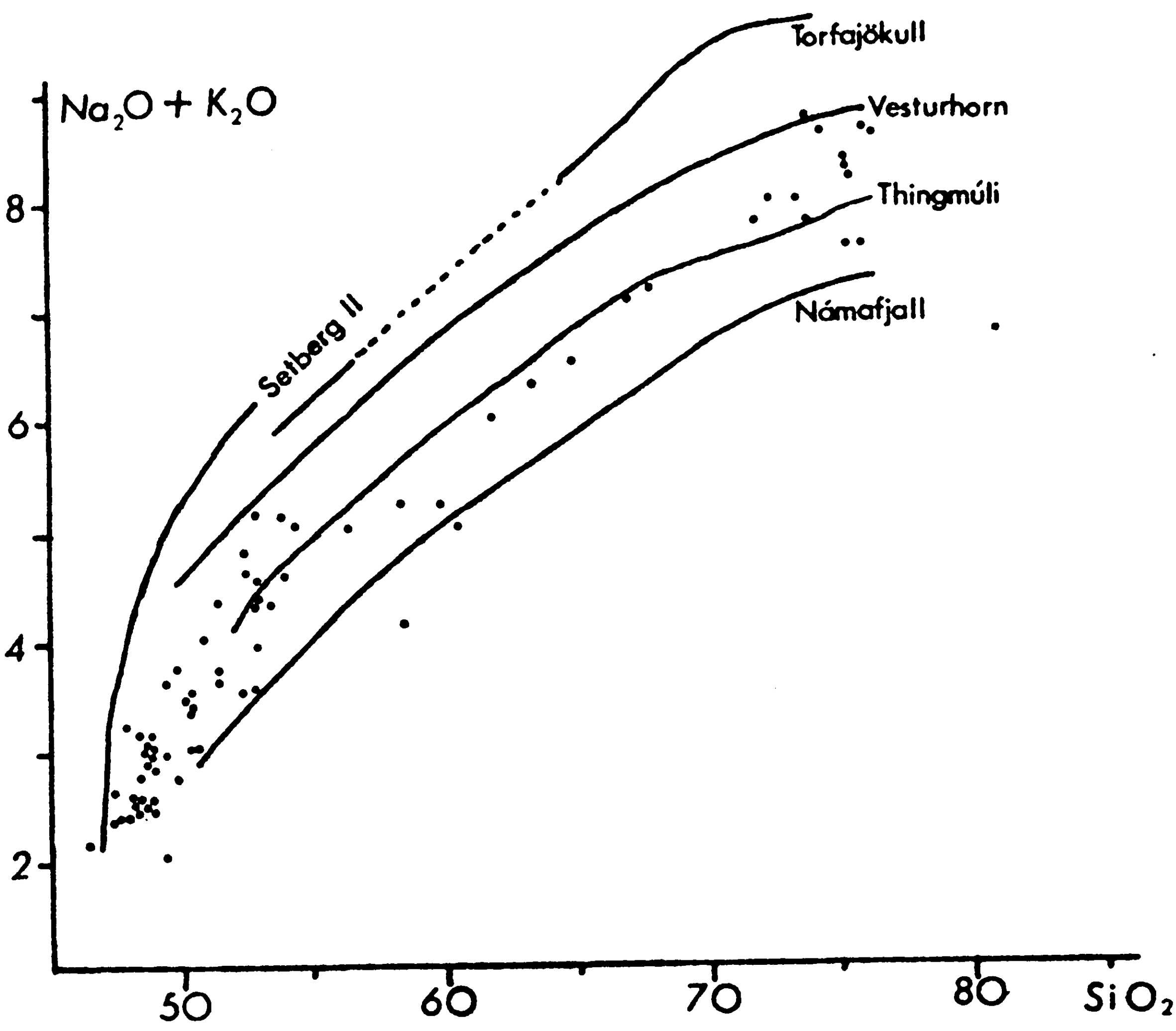


Fig.8.1

Total alkalis versus silica content of samples from the Hafnarfjall-Skarðsheiði central volcano in comparison with the trends of Þingmúli (Carmichael, 1964), Vesturhorn (Roobol, 1969), Setberg II (Sigurðsson, 1970), Námafjall, Torfajökull (Grönvold, 1972).

Carmichael (1964)

Basaltic andesite	Andesite (Icelandite)		Rhyolite
52.7-55.9	59.3-64.5		69.4-75.7

Sigurðsson (1970)

Basaltic andesite	Icelandite	Rhyodacite	Rhyolite
53-57	60-67	66-70	68-75

Grönvold (1972)

Basaltic icelandesite	Icelandesite	Dacite	Rhyolite
52-56	56-63	63-69	69-76

Friðleifsson (1973)

Basaltic andesite	Icelandite		Rhyolite
50-57	57-67		67-77

Jóhannesson (1975)

Basaltic icelandite	Icelandite	Dacite	Rhyolite
52-56	56-63	63-69	69-77

Present work

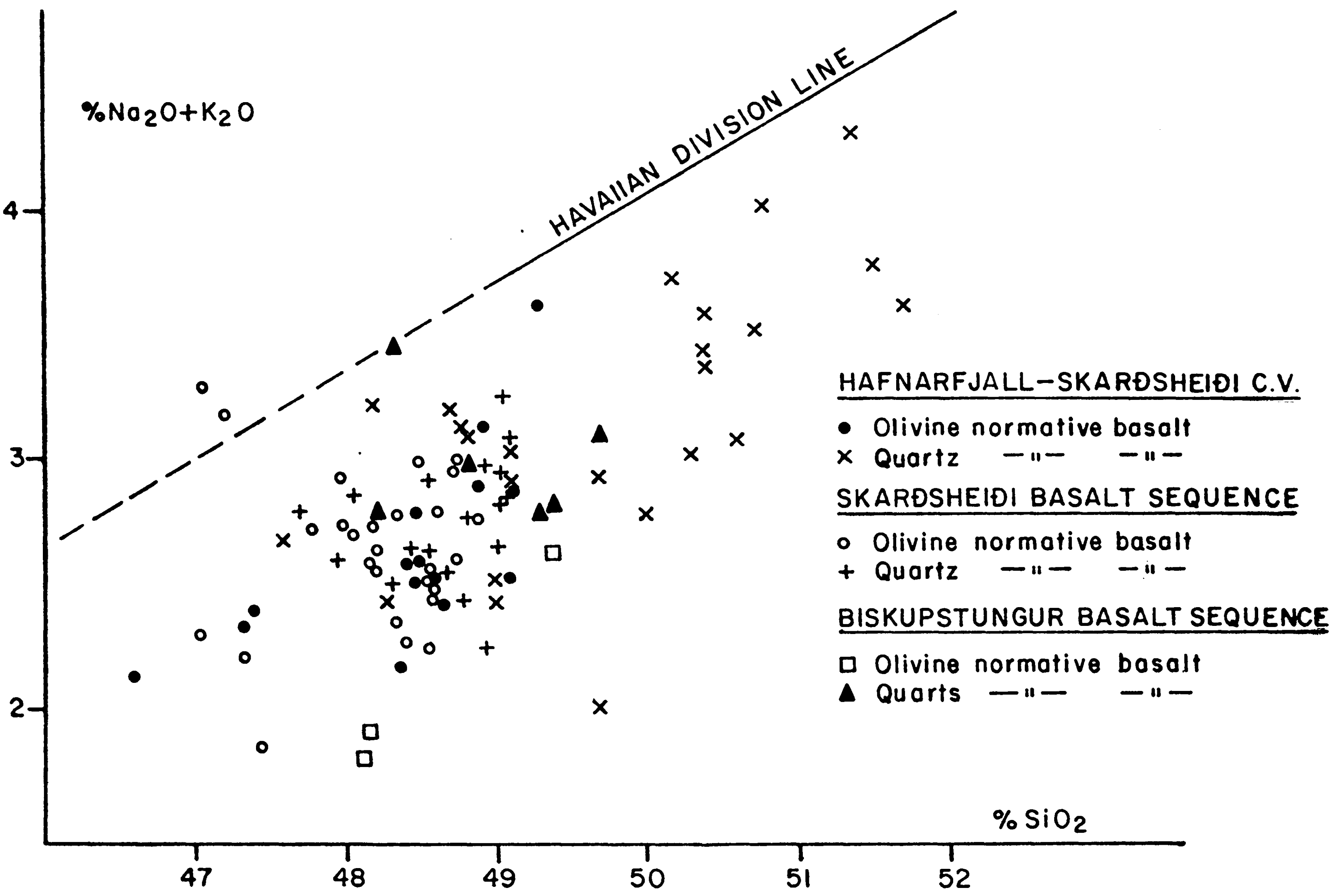
Basaltic andesite	Icelandite	Dacite	Rhyolite
52-56	56-63	63-69	> 69

Table 8.2

A comparison of rock nomenclature used by the above authors. The numbers refer to the appropriate silica values.

Fig.8.4

The total alkalis vs. silica plot of all analysed basalt samples. The Hawaiian division line taken from MacDonald and Katusura (1964).



%Na_2O+K_2O
4
3
2
HAVAIIAN DIVISION LINE
%SiO_2
47
48
49
50
51
52
HAFNARFJALL–SKARÐSHEIÐI C.V.
● Olivine normative basalt
× Quartz —"— —"—
SKARÐSHEIÐI BASALT SEQUENCE
○ Olivine normative basalt
+ Quartz —"— —"—
BISKUPSTUNGUR BASALT SEQUENCE
□ Olivine normative basalt
▲ Quarts —"— —"—

Fig.8.4

Carmichael (1964) distinguishes between olivine tholeiites and tholeiites on petrological criteria where the former includes more than accessory amount of olivine. Similar methods of distinction were used by Grönvold (1972) and Friðleifsson (1973). The identification of olivine in the groundmass was made difficult by small grain size as well as a considerable alteration of many rock samples from the research area. The distinction in this study between olivine tholeiite and tholeiite was therefore made on Yoders and Tilley´s (1962) CIWP normative classification where the former contained normative olivine. The division between these two basalt groups is to some extent controlled by the Fe_2O_3/FeO $+Fe_2O_3$ ratio of the rock samples. To counter secondary alteration (oxidation) this ratio has been fixed at 0.25, which is a mean value of over 50 analysed fresh basalt samples from the Reykjanes-Langjökull rift zone (Jakobsson, 1972). This method has also been used by Jóhannesson (1975). The normative compositions of the analysed samples are given in appendix along with the chemical compositions.

8.2 Petrography

Most of the samples are fine grained, especially those of differentiated compositions which are extremely fine grained or glassy. The majority (c.75%) of the rocks contains (micro)phenocrysts which vary from a single crystal up to 40% of the rock, but are generally < 2%.

Table 8.3 is a summary of the relevant petrographic features where the main emphasis is laid on bringing out the presence or absence of phenocryst species as well as the crystallization mode of the ore minerals. A note was made of the presence of olivine in the groundmass where recognized.

Feldspar is by far the most common phenocryst phase occurring in all the rock types. These are usually strongly zoned and frequently contain pockets of groundmass crystals indicating rapid growth. Within the basalt range they often occur in glomeroporphyritic clusters, but are more rarely observed in the intermediate to acid compositions.

Olivine phenocrysts are mostly confined to olivine tholeiites and slightly (< 1%) quartz normative tholeiites. It occurs in two basaltic andesites and one icelandite. Euhedral microphenocrysts were identified in four of the rhyolites, in two of which they were attached to ore microphenocrysts. One sample (H34) exhibited skeletal growth in the olivine phenocrysts.

Olivine is commonly found in the groundmass in the olivine tholeiites and more rarely in the quartz tholeiites. It has not been identified in the groundmass of the differentiated rocks under discussion.

Clinopyroxene is found as a phenocryst phase in all rock

Table 8.2

Relevant petrographic features of rock samples from the Hafnarfjall-Skarðsheiði central volcano (CV), Hvalfjörður lenticular lava unit in Heiðarhorn (H) and Skarðshyrna (S) and samples from Biskupstungur (B).

M = Microphenocryst

R = Rare (less than 5 crystals in a thin section)

Sample	Phenocrysts				Groundmass		
No.	Plag.	Ol.	Px.	Ore	Euhedr. ore	Interst. ore	Ol.
OLIVINE NORMATIVE THOLEIITES							
CV11	X		X		X		
CV30		X		MR		X	X
CV9	MR				X		
CV26		XR				X	X
CV35	X					X	X
CV2	XR					X	X
CV13						X	X
CV80	X	X	X			X	X
H1	X					X	
H2	X	X				X	X
H4	X					X	
H 29	XR					X	
H30	M					X	
H 41	XR				X	X	
H7	X	XR				X	
H11	X		XR			X	
H38	XR				X		
H10	X					X	
H17	MR				X	X	
H19	M		M			X	
H26	M					X	
H 35	X		XR			X	X
H40	XR					X	
H12	X	XR				X	X
H13	X					X	X
H14	XR					X	
H28	X				X		
H15	M				X	X	
H 21	MR				X		
H 27	X	X				X	
H 31		XM				X	X
H32	XR	X				X	X
H34	X	X				X	X
S15		XR				X	
S 37	M				X		
B1	X					X	X
B4	X	X	X			X	X
B7	X		X			X	X
B9	X	XR				X	X
QVARTZ NORMATIVE THOLEIITES							
CV27	MR				X	X	
CV24	M				X	X	
CV14	X		X			X	
CV8					X	X	
CV4					X		
CV32	X	XR	XR		X	X	X
CV10	X	XR				X	X
CV23	XR					X	X

Sample	Phenocrysts				Groundmass		
No.	Plag.	Ol.	Px.	Ore	Euhedr. ore	Interst. ore	Ol.
CV29	XM		M	MR	X		
CV16					X	X	
CV5						X	
CV6					X		
CV1					X		
CV4					X	X	
CV19			XR		X		
CV12					X		
CV7	M				X		
CV15	X	X	XR			X	X
CV44	X				X		
CV33					X	(X)	
CV25	M		M		X		
CV17					X		
CV81					X	X	
CV82					X		
H3	X					X	
H5	X	X			X	X	
H6		X			X	X	
H8	XR	XR				X	
H9	X					X	
H16	XR	XR	MR		X		
H18	MR	XR	XR		X		
H20	MR				X	X	
H22		XR			X	X	
H24	XR		XR			X	
H25					X	X	
H36	X					X	
H42	MR					X	X
H23					X		
S34					X		
S41					X	X	
S45					X		
S47					X	X	
B2					X		
B3	MR			MR	X		
B5	XR					X	
B6	X		XR		X		
BASALTİC. ANDESİTES							
CV50					X		
CV39	XM	XR	X		X		
CV47	X		X		X		
CV45	M		M	M	X		
CV37					X		
CV40					X		
CV41	M		MR	MR	X		
CV53	X	X	X	X	X		
CV42	X		XR	MR	X		
CV55	X				X		
CV83	XR			MR	X		

Sample	Phenocrysts				Groundmass		
No.	Plag.	Ol.	Px.	Ore	Euhedr. ore	Interst. ore	Ol.
CV46					X		
CV84	X				X		
ICELANDITES							
CV52	M		MR		X		
CV49					X		
CV51	XR				X		
CV48					X		
CV59	X	XR	M	M	X		
CV54	MR		MR		X		
DACITES							
CV60	X		M	M	X		
CV58	R		M	MR	X		
CV61	XR			M	X		
CV57	M		M		X		
CV62	M		M		X		
RHYOLITES							
CV63	MR				X		
CV70	M		MR	M	X		
CV74		MR		MR	R		
CV85	M	M		MR			
CV64					X		
CV71	X	XR			X		
CV75					X		
CV66	X				X		
CV73	X	XR			X		
CV67	XR				X		
CV68	X		MR		X		
CV65	X				X		

compositions although not abundantly. Neither orthopyroxene nor pigeonite were identified as phenocrysts but may be present in the groundmass. The clinopyroxenes in the acid rocks show a very high relief and a slight pleochroism.

The Fe-Ti oxides (ore) show a progressive change with composition where the interstitial anhedral ore grains predominating in the olivine tholeiites gradually give way to early crystallizing euhedral ore in the quartz normative tholeiites, and become the predominating phase above c. 50% silica. Ilmenite rods occur in the basalt range but are rarely present in the differentiated rocks. The euhedral ore is very abundant in the basaltic andesites but gradually diminishes with increasing silica to interspersed minute ore grains in the rhyolites. Euhedral ore is present as rare microphenocrysts in basaltic andesite to rhyolite compositions. These are frequently to be found attached to plagioclase and pyroxenes and in rhyolites to olivine (micro)phenocrysts.

Petrographic features of the rock samples resemble closely those of Þingmúli (Carmichael, 1964). He postulated that the Þingmúli chemical trends were controlled by the fractional crystallization of the phenocryst species present in the magmas. In particular, the coincidence of the first appearance of iron-titanium oxide phenocrysts with a sharp break in chemical trends at the basaltic - basaltic andesite boundary led Carmichael to postulate that these oxides were the main fractionating phase in the differentiated rocks.

An increase in the modal abundance of the ore minerals with time in the 1970 Hekla lava eruption without a concominant increase in iron and titanium, led Sigvaldason (1972) to suggest that atmospheric oxidation was an important factor in the modal content of the ore minerals. This assumed effect of atmospheric oxidation may be consistent with the observation (Grönvold, 1972) that the very fine grained and glassy (sub-glacial) volcanics of Kerlingafjöll lack the two size-fraction ore minerals, so distinct in Þingmúli. In Hafnarfjall-Skarðsheiði volcano, a distinct two size-fraction ore minerals in the groundmass were not observed. However, a large size variation in the ore minerals is notable as a result of slightly prolonged groundmass crystallization within individual intermediate extrusives.

8.3 Geochemistry

a. Geochemical setting

Miyashiro (1971) pointed out the narrow chemical composition range of basalts along the Mid-Atlantic Ridge and Brooks and Jakobsson (1974) showed that, in comparison with Mid-Ocean ridge basalts (MORB), the more Fe- and Ti-rich basalts in Iceland (FETI), have broader compositional dispersion and are relatively enriched in LIL elements (such as K,Ti,P,Rb,Cs,Sr,Ba,Zr and U). Furthermore the FETI basalts are also light REE-enriched and have higher radiogenic Sr and Pb contents (Sigvaldason et al., 1974; Brooks et al., 1974; Schilling, 1973; O´Nions and Grönvold, 1973). The boundary between Iceland and the ocean ridge south of Iceland is compositionally gradational over 400 km (Schilling, 1973; Hart et al., 1973) but the corresponding boundary to the north occurs abruptly across the Tjörnes Fracture Zone (Sigvaldason and Jakobsson, 1974). Within Iceland itself Jakobsson (1972) identified a spatial distribution of basalts along the volcanic zones in Iceland, with olivine tholeiite compositions predominant along the Reykjanes-Langjökull zone and quartz tholeiites characterizing the northern part of the eastern zone; towards Torfajökull a gradation to transitional basalt occurs and thoroughly alkali basalt predominates in the vicinity of Vestman Islands in the south. The Snæfellsnes Fracture zone is also characterized by alkali olivine basalt. An apparent correlation exists between basalt chemistry and crustal thickness; this has been interpretated as implying that alkali basalts originated from greater depths than tholeiites. Brooks et al., (1974) and Sigvaldason et al., (1974) have shown that LIL element dispersion tends to be maximised in the vicinity of the Kverkfjöll area at the northern perimeter of Vatnajökull.

Whereas the spatial distribution of basalt compositions is reasonably well known along the Neovolcanic zones, their geochemical evolution with time is still little understood. O'Nions and Pankhurst (1973) note an apparent secular decrease in the $^{87}Sr/^{86}Sr$ ratio from Tertiary times to Recent. Jóhannesson (1975) suggests that during the last 6 m.y. a progressive geochemical change occurred within the Langjökull-Reykjanes spreading axis, giving rise to a notable progressive increase in Al and a decrease in Fe,Ti and most trace elements.

Geochemical data on Icelandic central volcanoes has been fairly well documented. With the exception of a few volcanoes, which show an overall enrichment in total alkalis with respect to silica content (e.g. Vesturhorn (Roobol, 1969), Setberg II (Sigurðsson, 1970) and Torfajökull (Grönvold, 1972), the majority follow the well established Þingmúli trend (Carmichael, 1964).

The Hafnarfjall-Skarðsheiði is the seventh comprehensively analysed central volcano of the Þingmúli type, and in addition reconnaissance rock analysis define a Þingmúli trend in up to twenty other volcanoes.

Prior to this study, the geochemical trends of central volcanoes, formed within the Reykjanes-Langjökull rift zone, were known from Húsafell (Grönvold, 1972) and Esja (Friðleifsson, 1973), both of which succeeded Hafnarfjall-Skarðsheiði in age. During the course of this study, the geochemical trends of the Hallarmúli, Reykjadalur and Laugardalur central volcanoes were published (Jóhannesson, 1975). The chemical trends of these five centres are analogous to that of Þingmúli.

b. The Hafnarfjall-Skarðsheiði central volcano

The primary objectives of a comprehensive analysis of the central volcano were 1) to establish its geochemical trend, and 2) to seek chemical anomalies which in some way might be associated with the anomalous tectonic setting of the central volcano (c.f. chapter 6).

Sampling of the whole range of chemical compositions was attempted, especially within the intermediate to acid rocks. Biased sampling may, however, have occurred due to the avoidance of altered materials within the more basic compositions (olivine tholeiites). The persistently xenolithic nature of the voluminous intermediate rocks of the Brekkufjall phase also restricted the sampling in that composition range.

Most samples show in thinsection some degree of alteration, but the limited scatter in elements easily removed (or added) during hydrothermal alteration (e.g. Na, K, Al) implies no marked change in composition. However, two rhyolite flows in Árdalsgil (CV66 and CV73) and a dacite in Mófell (CV61) show a marked depletion in Al,Na,Sr and Zn and an enrichment in K,Si and Rb, as a result of hydrothermal alteration. These samples were omitted from figs.8.5 and 8.6 and 8.8.

The variation in major and trace element abundances plotted against silica is shown in fig.8.5 and fig.8.6. Distinction is made between a) porphyritic rocks (> 10% phenocrysts), b) coarse grained intrusive rocks and c) aphyric rocks.

The chemical trends show an apparent chemical continuity in all elements, with the notable exception of Al (see later). The

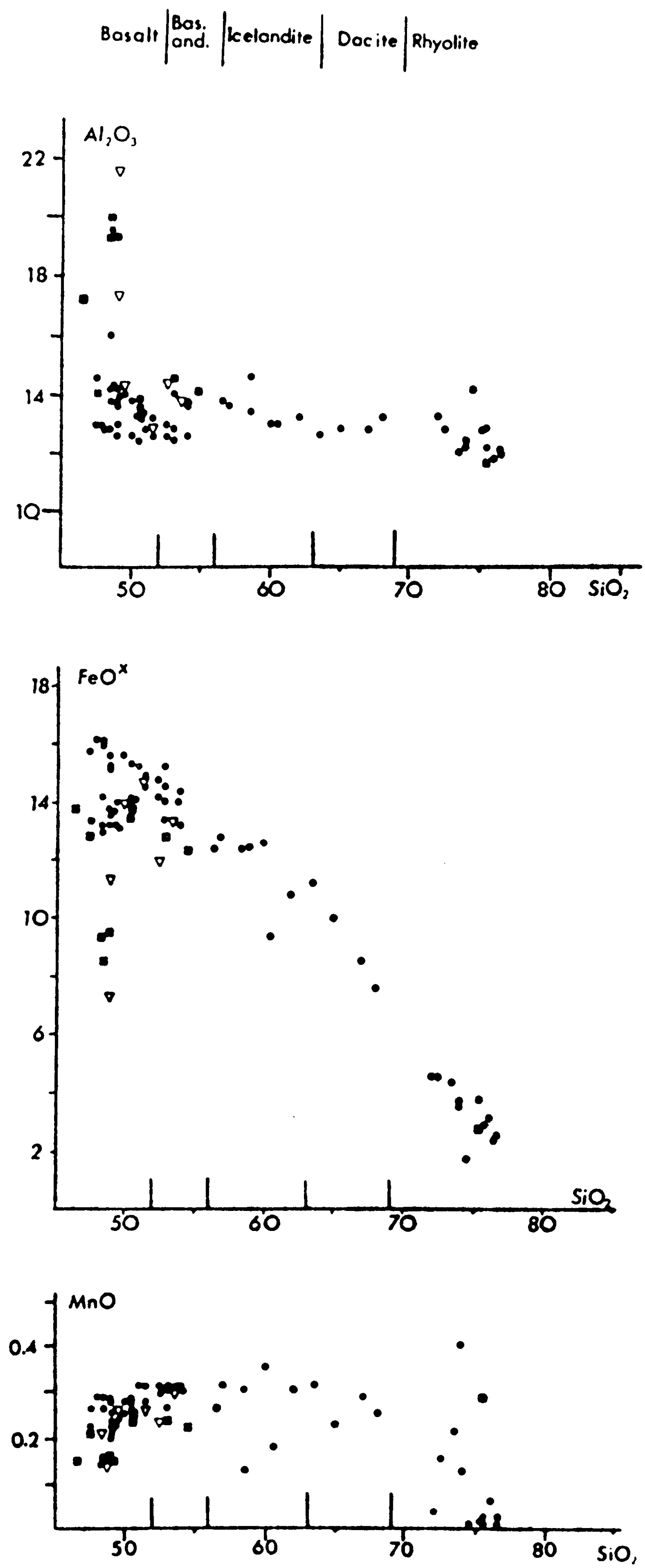
Fig. 8.5

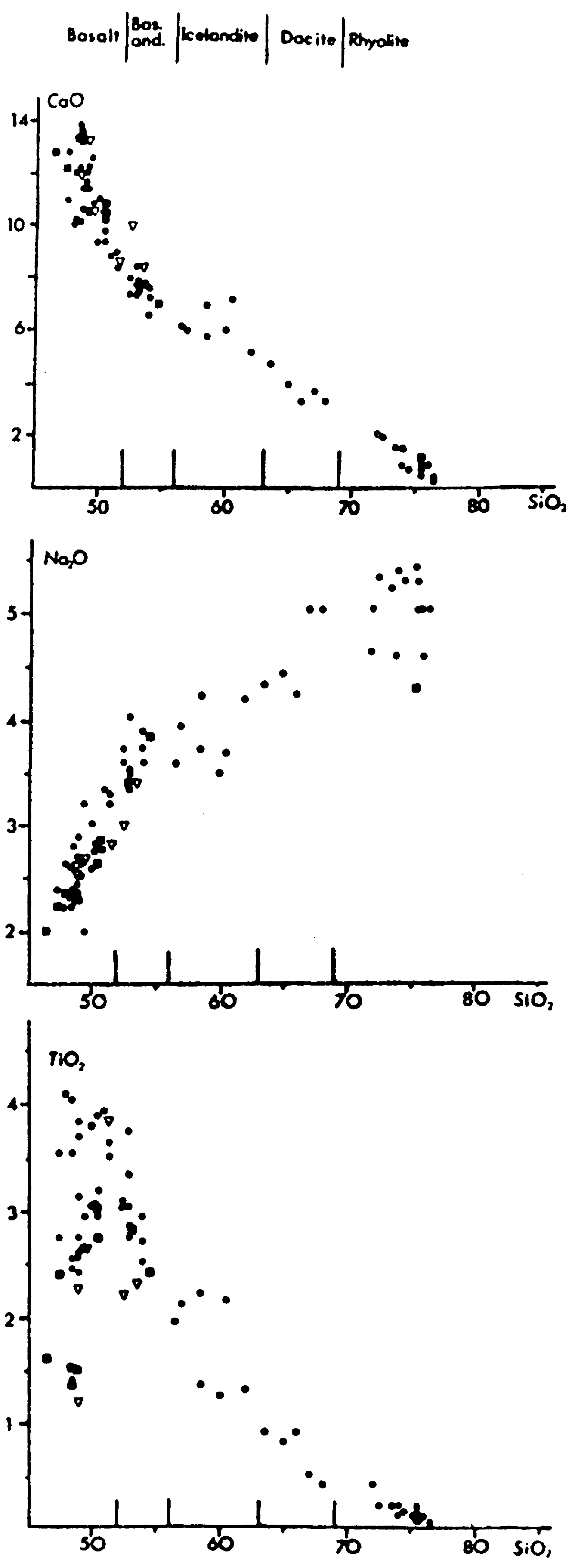
Major oxides plotted against silica of samples from the Hafnarfjall-Skarðsheiði central volcano.

Filled circle = aphyric rock

Filled square = coarse grained intrusion

Open triangle = porphyritic rock


Basalt
Bas. and.
Icelandite
Dacite
Rhyolite
Al_2O_3
22
18
14
10
50
60
70
80
SiO_2
FeO^x
18
14
10
6
2
SiO_2
50
60
70
80
MnO
0.4
0.2
50
60
70
80
SiO_2



Basalt
Bas. and.
Icelandite
Dacite
Rhyolite
CaO
14
10
6
2
50
60
70
80
SiO2
Na2O
5
4
3
2
50
60
70
80
SiO2
TiO2
4
3
2
1
50
60
70
80
SiO2

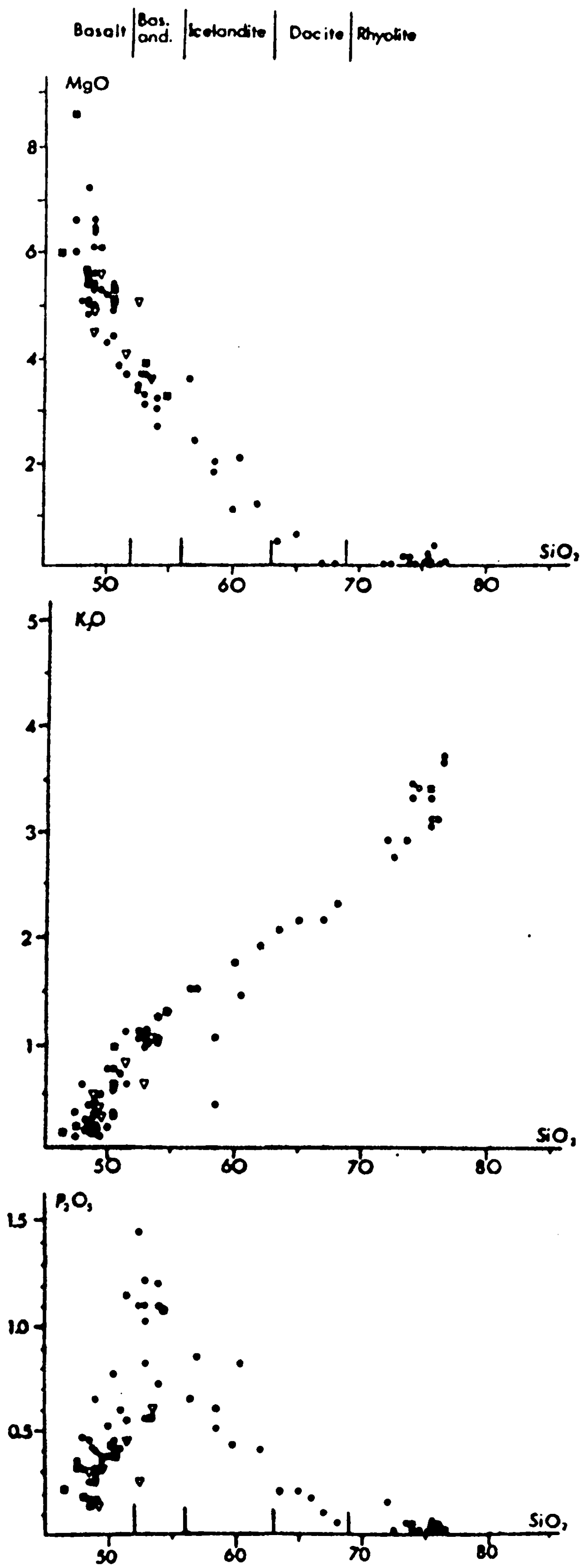

Basalt
Bas. and.
Icelandite
Dacite
Rhyolite
MgO
SiO2
K2O
SiO2
P2O5
SiO2

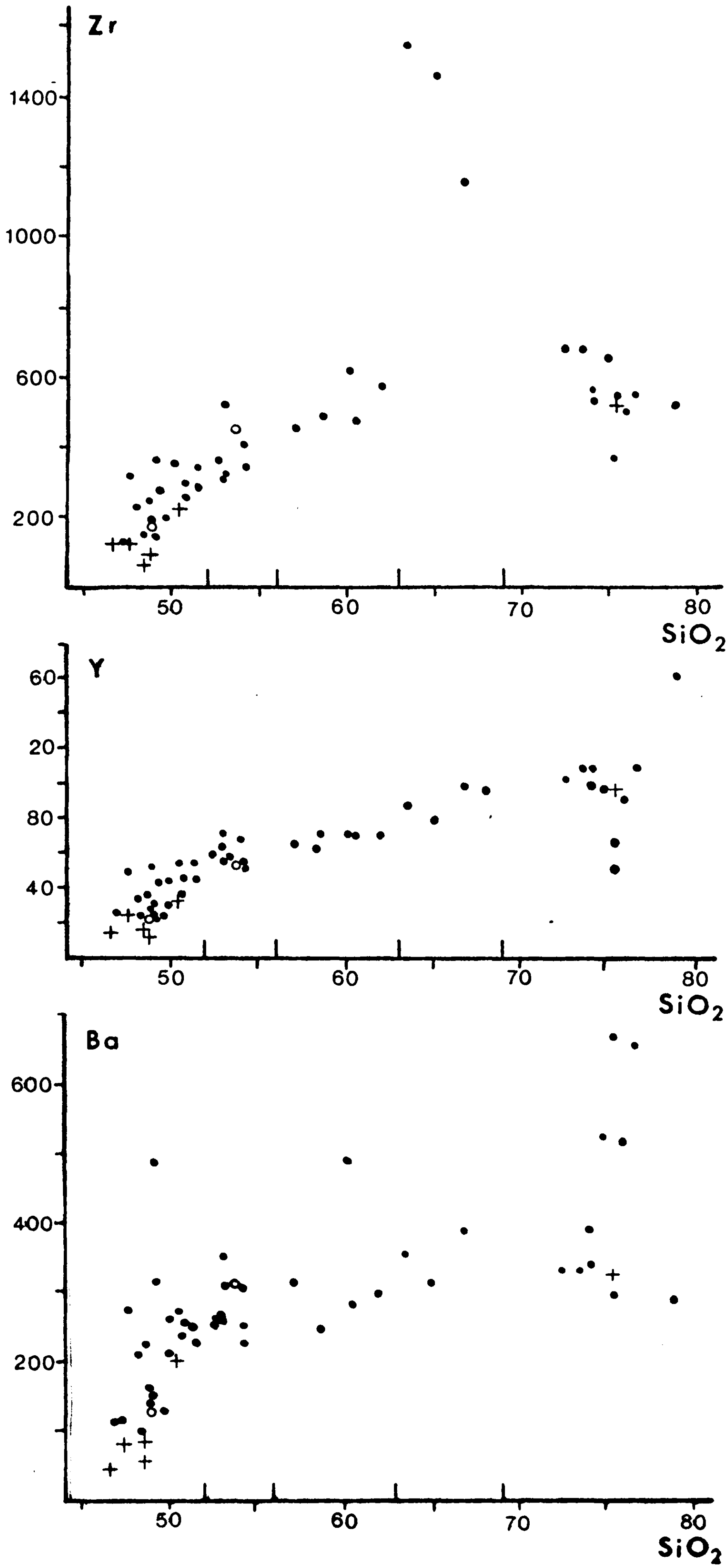
Fig.8.6

Trace elements plotted against silica of samples from the Hafnarfjall-Skarðsheiði central volcano.

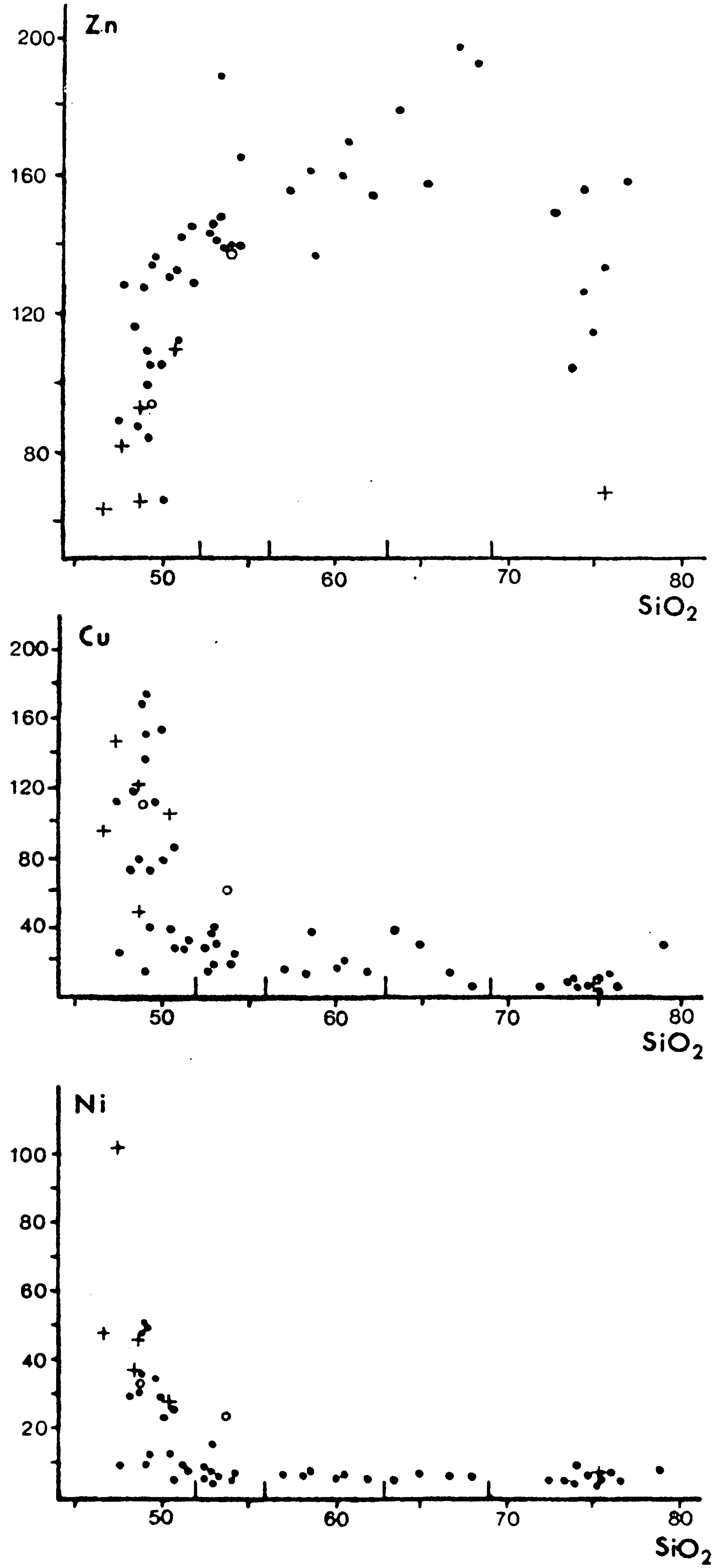
Filled circle = aphyric rock

Open circle = porphyritic rock

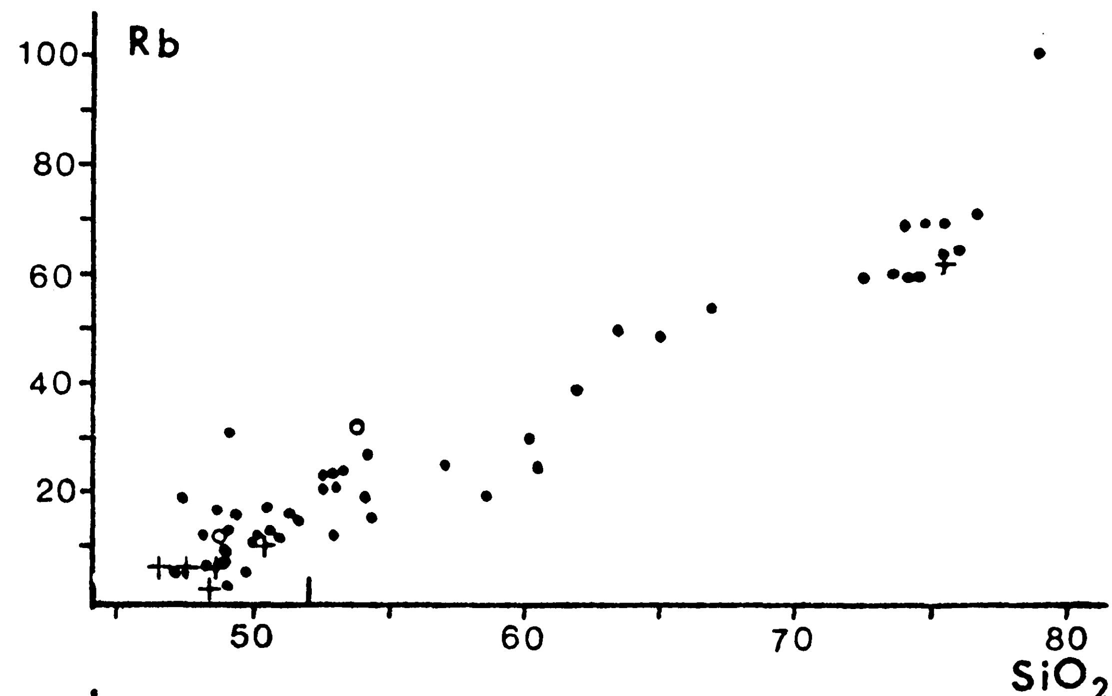
cross = coarse grained intrusion

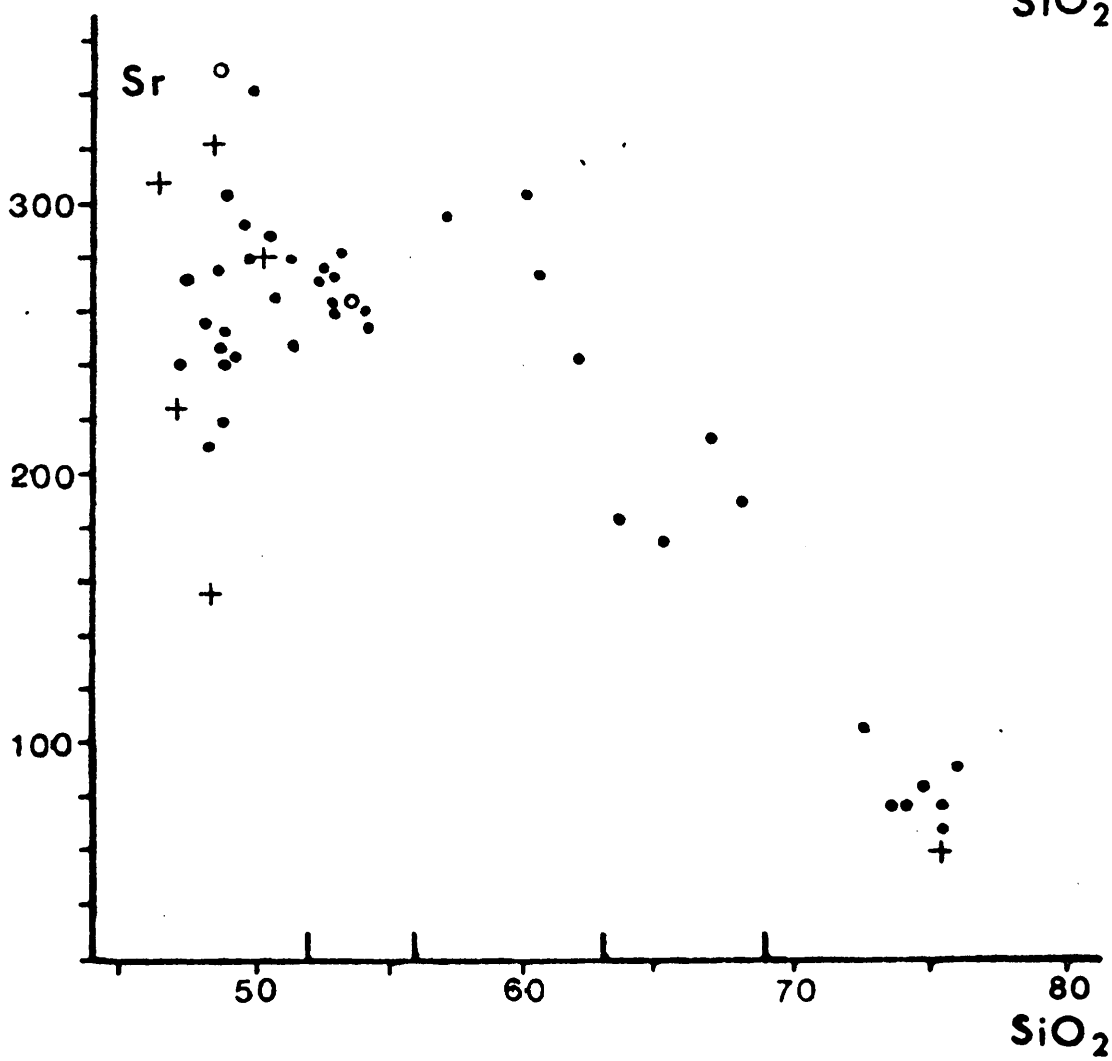


Zr
1400
1000
600
200
50
60
70
80
SiO2
Y
60
20
80
40
50
60
70
80
SiO2
Ba
600
400
200
50
60
70
80
SiO2



Zn
200
160
120
80
50
60
70
80
SiO2
Cu
200
160
120
80
40
50
60
70
80
SiO2
Ni
100
80
60
40
20
50
60
70
80
SiO2


Rb
100
80
60
40
20
50
60
70
80
SiO2


Sr
300
200
100
50
60
70
80
SiO2

trends (figs.8.5 and 8.6) show gradual and/or distinct breaks in slope at specific silica intervals as summarized in table 8.7.

The first break at about 50% silica, is most notable for the decrease of Al and Ca and an increase in Fe,Ti,Mn,Na,Rb,Sr and Zn at constant silica towards the break. Petrographically the break coincides with the transition from late to early crystallization of the ore groundmass phase, along with the near disappearance of olivine as phenocrysts in the groundmass.

The second break (51% silica) is only observed in Mg,Cu and Ni which show a sharp decrease at constant silica towards the break.

The third break (52% silica) is most marked by the reversal of Ti and P from a strong enrichment to an equally strong depletion, and K,Y,Zn,Ba,Zr and Ca experience a more rapid silica increase. Fe shows a complicated pattern in that it stays roughly constant with increasing silica up to the break where it decreases sharply from c. 15% to less than 13% at constant silica. Petrographically this break marks the appearance of ore as a microphenocryst phase.

The fourth break (c. 56% silica) is most clearly characterized by the reversal from a gentle increase to a sharp decrease in Sr. In addition Na shows a slower increase and Ti a slower decrease with respect to silica, whereas Rb shows a slightly faster increase.

The fifth break (c. 60% silica) is only observed in total iron (FeO^x) which remains constant at about 12.5% until the break occurs but thereafter falls sharply towards the rhyolite compositions. This pattern differs from that of Þingmúli (Carmichael, 1964) and Kerlingafjöll (Grönvold, 1972) where iron has been shown to decrease rapidly to about 8% from basaltic andesites to 60% and 65% silica (respectively) and to be followed at higher silica values by a more

% SiO_2	MgO	K_2O	P_2O_5	CaO	Na_2O	TiO_2	Al_2O_3	FeO^x	MnO	Rb	Sr	Cu	Ni	Y	Zn	Ba	Zr
50				(X)	X	(X)	X	X	X	X	X				(X)		
51	X											X	X				
52		(X)	X	X		X	X	X						X	X	X	(X)
56					X	X	X			X	X						X
60								X									
63							X										X
70	X	X	X	(X)	(X)	X	X			(X)	(X)			(X)	X	(X)	X

Table 8.7 The approximate silica values of the breaks in the trends of the major and trace elements of the Hafnarfjall-Skarðsheiði central volcano.

gentle decrease. Carmichael attributes the rapid iron decrease to fractional crystallization of magnetite to about 60% silica where the magnetite became suppressed as a major crystallizing phase, and the reappearance of olivine as a fractionating phase.

Apart from the Hafnarfjall-Skarðsheiði central volcano such strong iron enrichment (c.f. figs.8.10 and 8.11) has only been noted in the Hallarmúli acid locality c. 30 km to the north. These two areas also show anomalously high Mn content in the differentiated rocks (up to 0.4%).

The sixth break (c.63% silica) is only observable in Al and Zr where Al changes from a slight decrease to a constant value. The three dacite rocks (63-68% silica) analysed for Zr show highly anomalous values of 1150-1550 ppm whereas the Zr values of the icelandites and rhyolites on either side do not surpass 700 ppm. A comparatively high Zr content (up to 900 ppm) has been found in Hallarmúli(Jóhannesson, 1975).

A distinct silica gap between dacite and rhyolite compositions (69-71% silica) is associated with the seventh break. A similar gap has been noted at slightly lower values (66-69% silica) in Reykjadalur volcano (Jóhannesson, 1975) and not to be present in Kerlingafjöll (Grönvold, 1972). A change in slope is apparent in most components, most markedly in Mg and P which stay constant with increasing silica whereas K appears to change its slope towards a faster increase with silica. Zn shows a sharp reversal from an increase to a sharp decrease in the rhyolites. Similar changes were observed in Kerlingafjöll and Reykjadalur central volcanoes.

The trends of the chemical components described so far show an apparent continuity and conform largely to other differentiation trends of Þingmúli type. However, a distinct dislocation of the differentiation trend is observed for Al within the basaltic andesite range, where the low-Al group ($<$ 13%) discernible in this range is a direct continuation of the trend shown by the basaltic compositions, whereas the higher-Al values ($>$ 13%) in the basaltic andesites (high-Al group) appear to be a continuation of the compositions shown by the differentiated rock compositions.

Plagioclase is the chief host for Al, along with Na and some of the Ca in the magma. Assuming the Al-dislocation in the basaltic andesites to be a reflection of an increase in the plagioclase component, a concominant increase in Na and Ca is to be expected. However, no apparent Na increase accompanies the Al increase from the low- to the high-Al group of the basaltic andesites (fig.8.8). Neither is an increase in Ca apparent , thus making the dislocation unlikely to have been controlled by plagioclase fractionation.

If the chemical trends are divided into groups on the same basis as Al (i.e. high- and low-Al groups), Fe,Ti and Mn contents of the basaltic andesites show similar attachments to the respective basaltic and differentiated trends as does Al. Fig.8.9 shows Fe and Ti contents of the high-Al group to be a direct continuation of the differentiated trend, and the same components of the low-Al group to be a continuation of the basalt trend. The progressive confinement of Mn values within the basalt field with increasing silica is a characteristic feature of the low-Al group, while the dispersed Mn values of the high-Al group is similar to the behaviour of that component in the differentiated rocks. The abundance as well as the dispersion of P (fig.8.5) is shown to increase towards the basaltic andesite range, on the one hand with the increasing silica of the

Fig.8.8

Sodium content of samples from the Hafnarfjall-Skarðsheiði central volcano plotted against silica. Same symbols as in fig.8.10, except;

+ = low-Al basaltic andesite

x = high-Al basaltic andesite

Fig.8.8

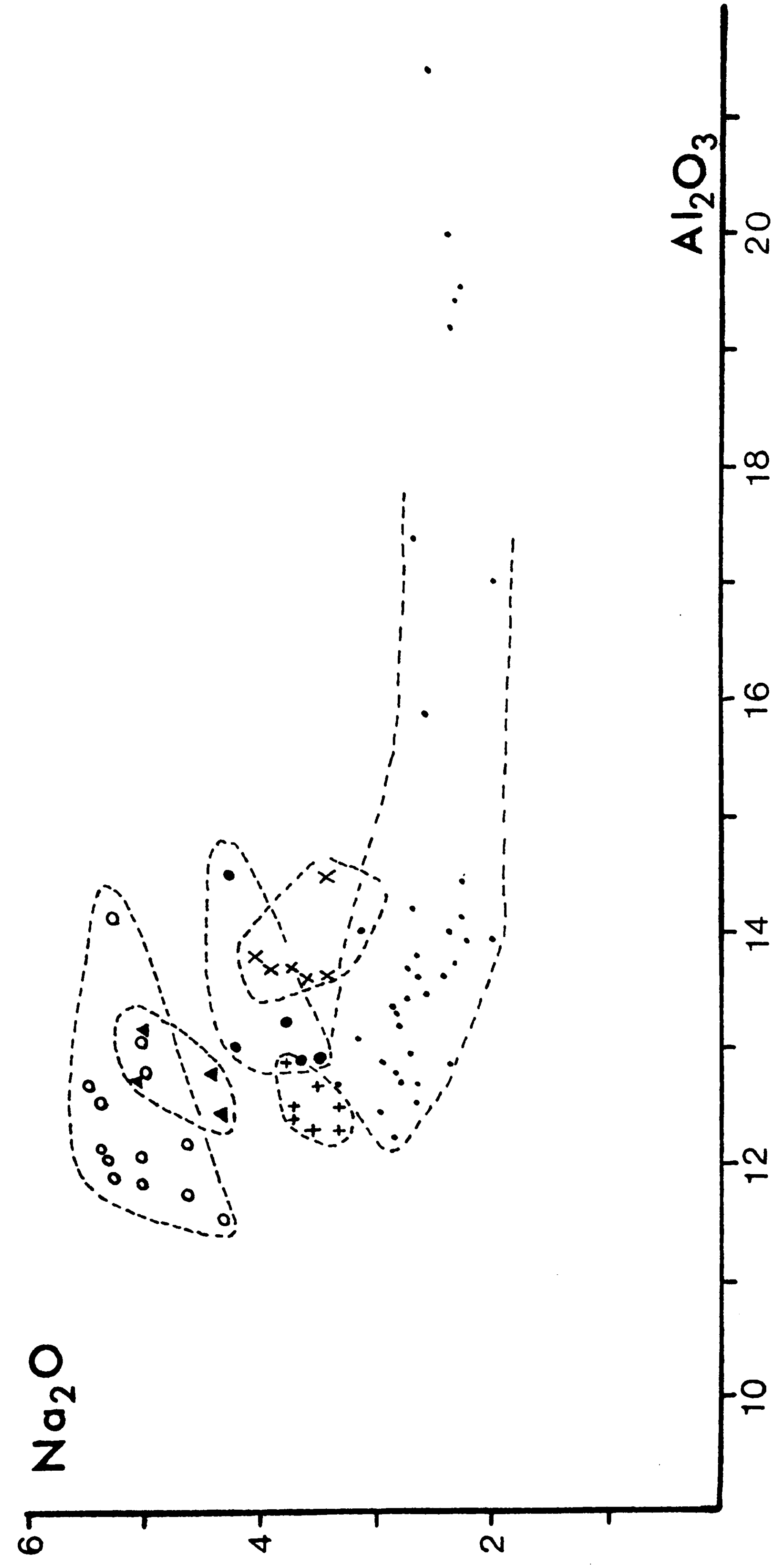


Fig.8.9

The compositional fields of

a) basalts and low-Al basaltic andesites (dots) and

b) high-Al basaltic andesites (broken lines) of the

Al, Ti, Mn and Fe oxides plotted against silica.

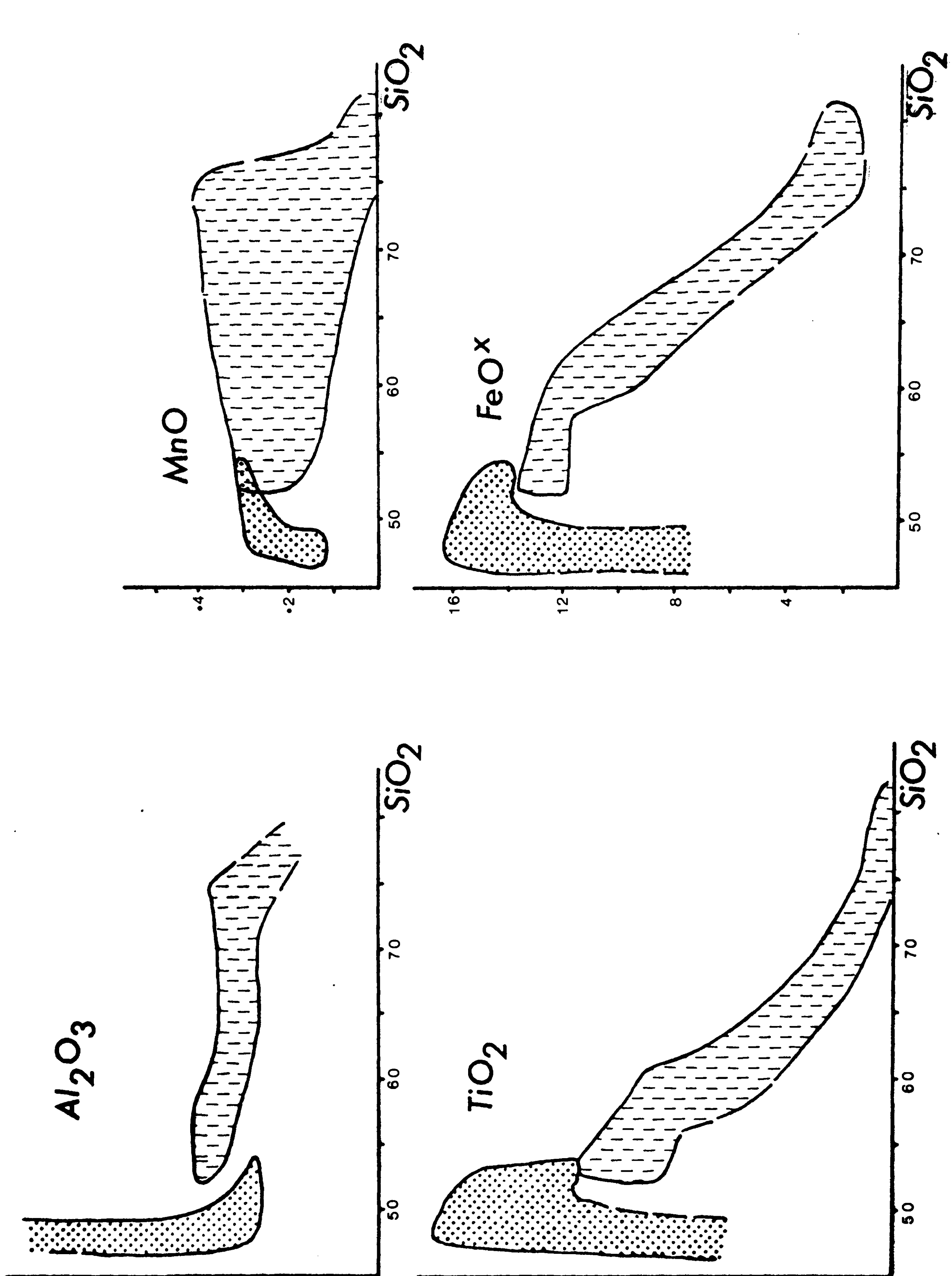

Al2O3
TiO2
MnO
FeOx
SiO2
SiO2
SiO2
SiO2
50
60
70
20
16
12
4
3
2
1
·4
·2
16
12
8
4

Fig.8.9

Fig.8.10

Magnesium content of samples from the Hafnarfjall-Skarðsheiði central volcano plotted against total iron, with a comparison with Þingmúli tholeiite trend (Carmichael, 1964) and Hawaiian alkali trend (McDonald and Katsura, 1964).

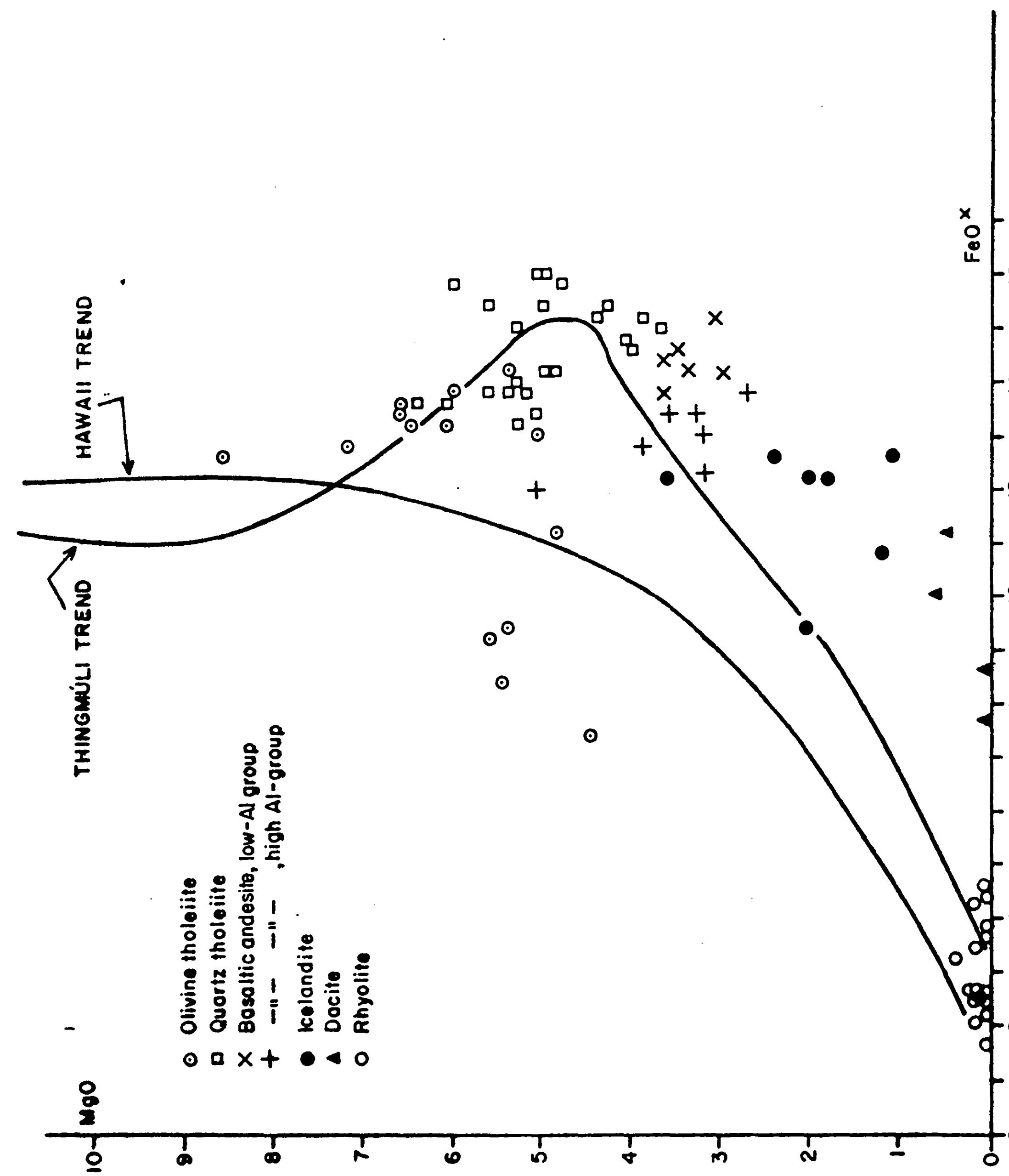

HAWAII TREND
THINGMÚLI TREND
MgO
FeO^x
Olivine tholeiite
Quartz tholeiite
Basaltic andesite, low-Al group
—"— —"— ,high Al-group
Icelandite
Dacite
Rhyolite
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16

Fig. 8.10

basalts on the other hand with the decreasing silica from the differentiated rocks, thus resulting in a near total overlapping of the two Al groups where the dispersion extends from c. 0.2 to 1.5%.

Although the Ca,Na and Mg oxide contents of the low-and high-Al groups do not indicate spatial distinction, marked differences are to be observed in the composition variations where the high-Al group shows much greater variation in these oxides than the low-Al group (see e.g. figs.8.8 and 8.10).

A clear division between the two basaltic andesite groups is, however, not evident from the available trace element data, except that Cu and Ni contents of the low-Al group do show a greater confinement to low values than does the high Al-group.

The geochemical data thus allows a distinction to be made between two separate rock suites within the Hafnarfjall-Skarðsheiði central volcano; a) the basic suite involving basalts and low-Al basaltic andesites and b) an acid suite involving a range from high-Al basaltic andesites to rhyolites. The significance of these two suites is discussed further in chapter 11.

There would not appear to be any clear spatial separation of the two chemically distinct basaltic andesite groups within the central volcanic area. However, as indicated in fig.11.2 there is a tendency among the differentiated volcanics, for the intermediate compositions to be more abundant in the west (Brekkufjall phase volcanics) and for rhyolites to predominate in the east (Skarðsheiði phase volcanics).

In general it has not been possible to identify geochemical distinctions between the volcanic products of one phase and the next during the evolution of the Hafnarfjall-Skarðsheiði lenticular lava

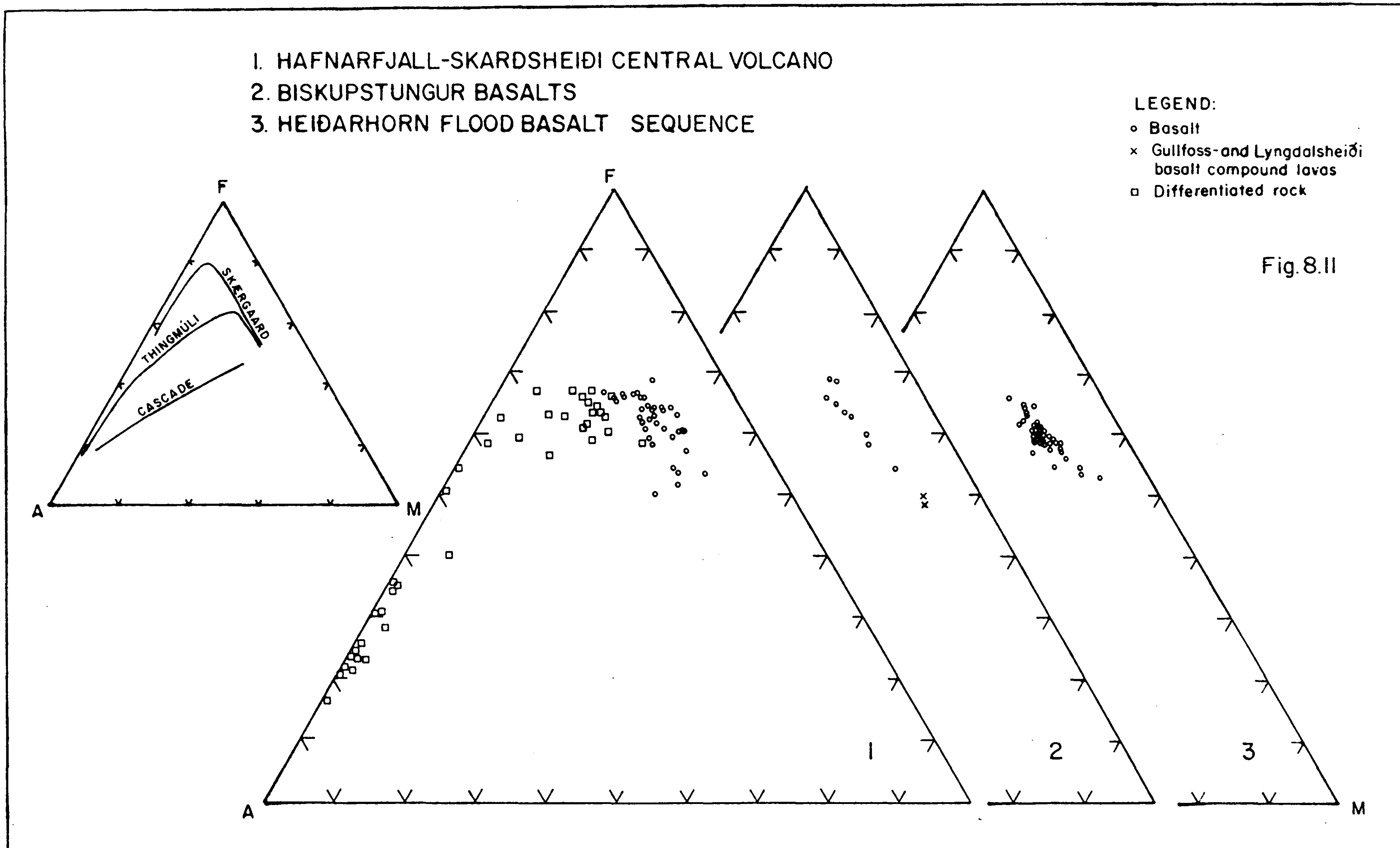

1. HAFNARFJALL-SKARÐSHEIÐI CENTRAL VOLCANO
2. BISKUPSTUNGUR BASALTS
3. HEIÐARHORN FLOOD BASALT SEQUENCE
LEGEND:
o Basalt
x Gullfoss-and Lyngdalsheiði basalt compound lavas
□ Differentiated rock
F
A
M
SKÆRGAARD
THINGMÚLI
CASCADE
1
2
3

Fig. 8.11

unit. The Brekkufjall phase dacites do, however, show anomalously high Zr-values while the Skarðsheiði phase rhyolites tend to be distinguished by higher Ba-values. A more thorough sampling of rocks of individual phases is needed before these characteristics can be verified.

c. <u>Basalt of the Hvalfjörður lenticular lava unit</u>

Extensive geochemical sampling was done in this lenticular lava unit in Heiðarhorn and Skarðshyrna in western Skarðsheiði (c.f. fig.3.26).

The criteria for the sampling may be summarized as follows:

a) The comprehensive geological data (c.f. chapter 4) points to low lava extrusion rate at the base of the unit where porphyritic lavas predominate, and to a high rate towards the upper part, as evidenced by the thin aphyric central volcanic lava flows.

b) It is reasonable to assume that the lavas were extruded within the limits of the Hvalfjörður fissure swarm, and are thus likely to represent magmas derived from a very localized sector of the mantle within a definite time interval.

c) The sample locality in Heiðarhorn and Skarðshyrna lies perpendicular to the locus of the most extreme magmatic activity within the lenticular lava unit (i.e. to the Hvalfjörður central volcano) and on the assumption that the degree of magmatic activity is likely to affect the chemical composition of extrusives, should represent a good cross section of such changes.

In Heiðarhorn (H) the sequence comprises 42 lavas (fig.8.12) of which 40 were analysed for major elements and fifteen for trace elements. In addition five samples in Skarðshyrna (S), about 2 km south of Heiðarhorn were analysed for major as well as trace elements.

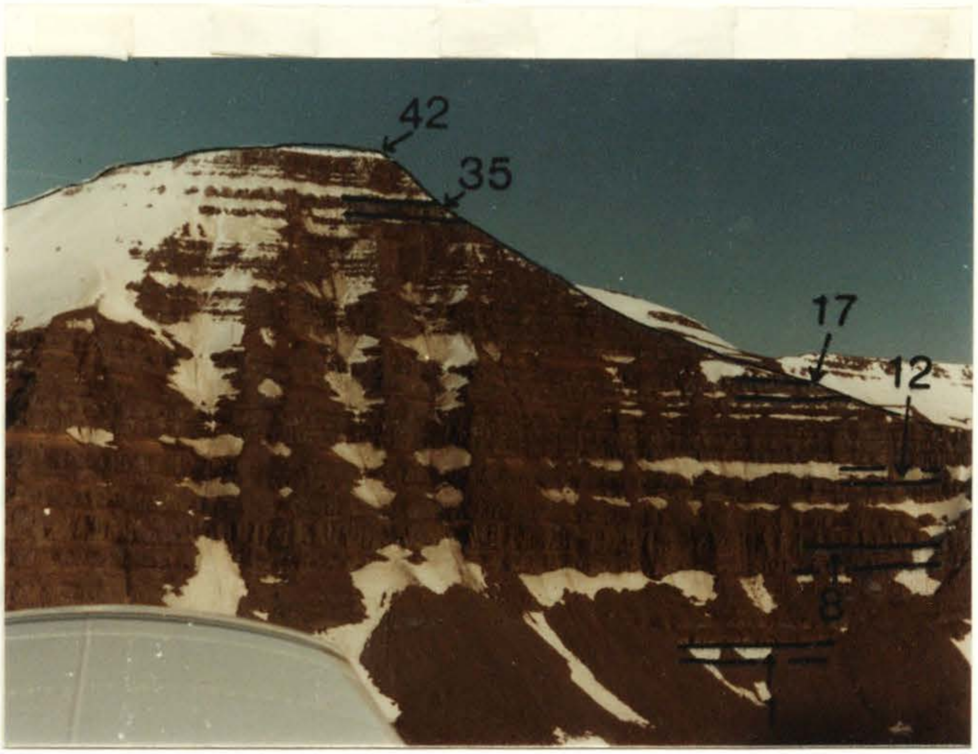
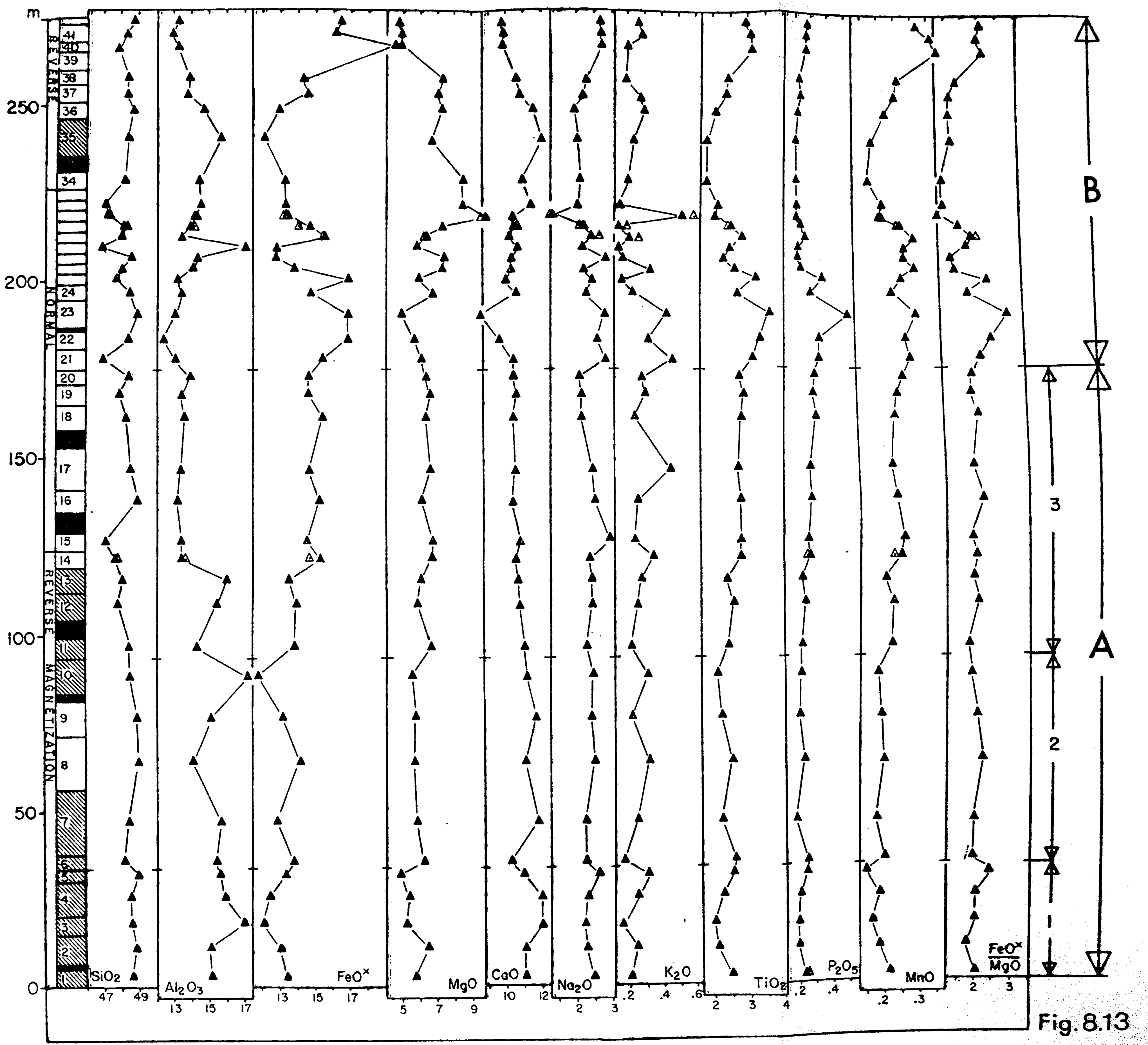


Fig.8.12

A view of the northern face of Heiðarhorn.
The numbers refer to the stratigraphical position
of some of the chemically analysed samples.

Fig.8.13

Major oxide variations plotted against the Heiðarhorn stratigraphic profile.
Shaded lavas contain more than 10% phenocrysts.



m
250
200
150
100
50
0
REVERSE
NORMAL
REVERSE MAGNETIZATION
41
40
39
38
37
36
35
34
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
SiO_2
47
49
Al_2O_3
13
15
17
FeO^x
13
15
17
MgO
5
7
9
CaO
10
12
Na_2O
2
3
K_2O
.2
.4
.6
TiO_2
2
3
4
P_2O_5
.2
.4
MnO
.2
.3
$\frac{FeO^x}{MgO}$
2
3
B
A
3
2
1

Fig. 8.13

The majority of the samples were found to contain some amygdales (mainly chabazite, thomsonite and minor scolecite). Two sets of five of the most zeolitized samples (H1,H14,H29,H30,H31) were analyzed where the zeolites had been separated from one set (open triangles) but not the other. A comparison (fig.8.13) between these two sets reveals insignificant variations in most elements except for slight differences in K, Al and Fe.

As indicated on the AMF diagram (fig.8.11) and in figs 8.14 and 8.15, the compositions of the Skarðsheiði basalts generally lie within the broad compositional limits of the Hafnarfjall-Skarðsheiði central volcanic basalts, although the latter does exhibit a narrower range in, and lower values of, Mg, Mn and Y.

The lower part of the Skarðsheiði basalts (H1-H20) exhibits a distinctly greater compositional uniformity than the upper part (H21-H42). Accordingly, this characteristic is used to divide the succession into a lower Group A and an upper Group B (fig.8.13). The distinction between the two groups can also be recognized in a Fe/Mg v. stratigraphic height plot (fig.8.13). The boundary between Group A and B occurs three lavas below the sequence of thin tholeiite flows assigned to the Hvalfjörður central volcano (chapter 4).

All major elements in Group A show a greater restriction in composition, specially in Mg, Ca, Ti and P. Although only about half the Skarðsheiði basalts were analyzed for trace elements, the same restriction in compositional dispersion of Group A lavas is evidenced especially in Y, Zr and Ba (fig.8.15). Group A lavas generally show higher Si, Ca, Al, Sr and Rb values than Group B lavas but concominantly lower values for other elements except for Na, K and Zn where the values overlap.

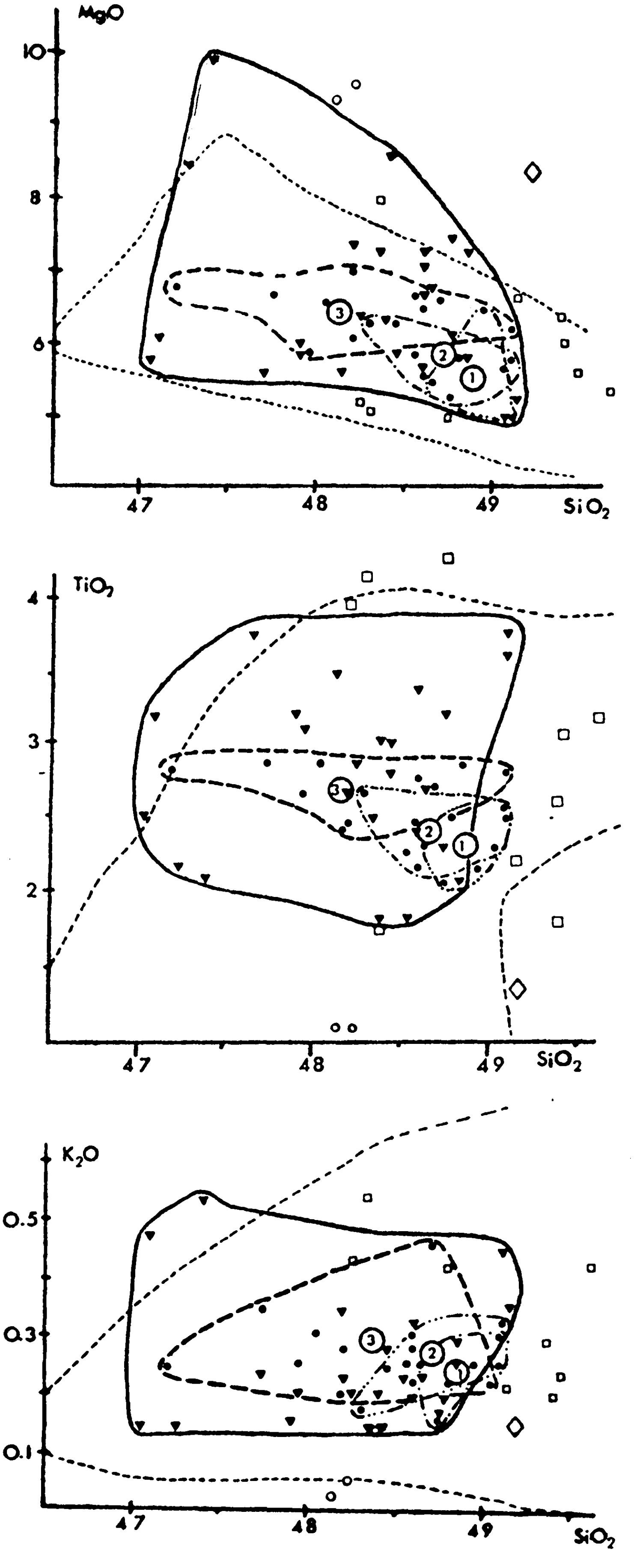
Fig.8.14

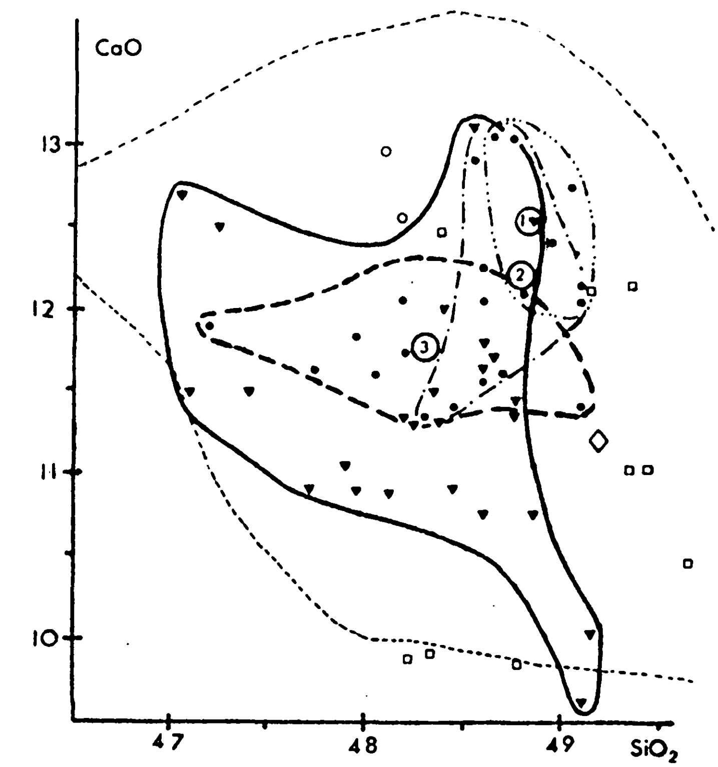
Major oxides of Skarðsheiði and Biskupstungur basalts plotted against silica.

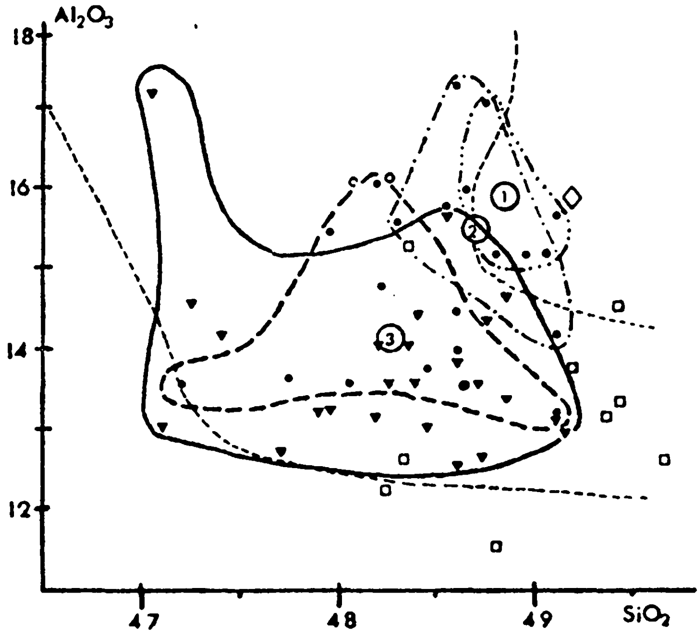
Thin broken line	=	Composition field of Hafnarfjall-Skarðsheiði central volcano.
Thick unbroken line	=	Compositional field of Group B lavas
Thick broken line	=	Compositional field of A3
Broken line with one dot	=	Compositional field of A2
Broken line with three dots	=	Compositional field of A1

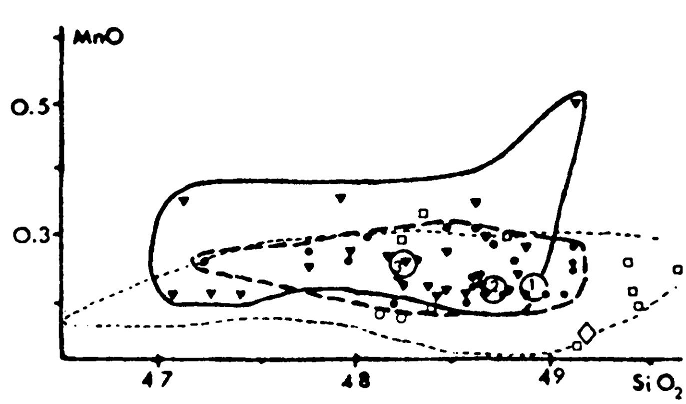
The encircled numbers refer to the respective A1, A2 and A3.

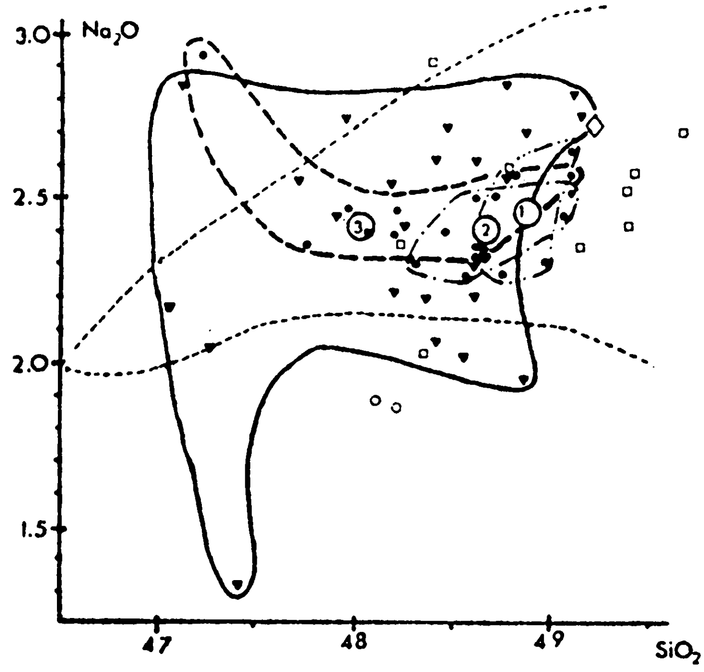
Filled triangle	=	Group B lava
Filled circle	=	Group A lava
Open square	=	Fell Formation, Biskupstungur
Open circle	=	Compound lavas, Biskupstungur
Open diamond	=	Average MAR composition


MgO
10
8
6
47
48
49
SiO2
3
2
1
TiO2
4
3
2
47
48
49
SiO2
3
2
1
K2O
0.5
0.3
0.1
47
48
49
SiO2
3
2
1

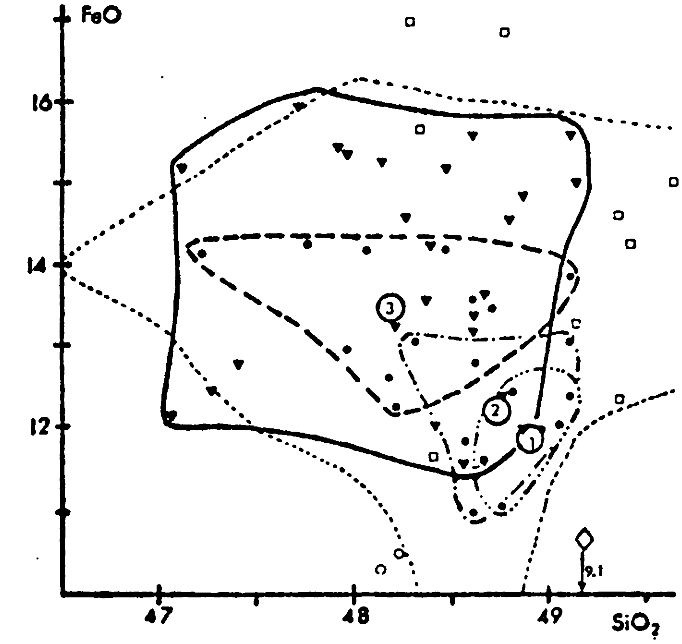

CaO
13
12
11
10
47
48
49
SiO_2
1
2
3


Al_2O_3
18
16
14
12
47
48
49
SiO_2
1
2
3

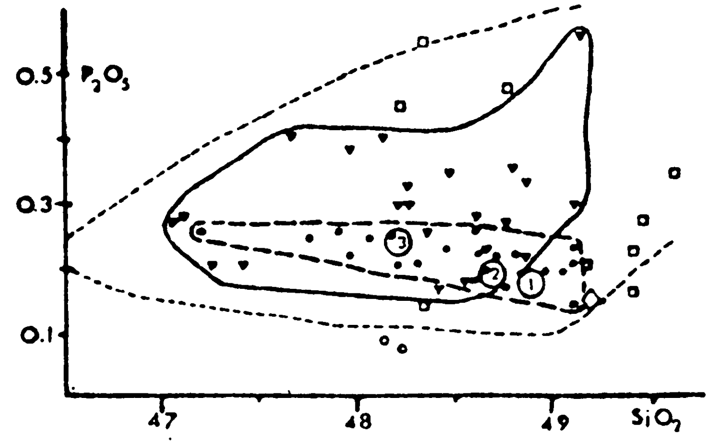

MnO
0.5
0.3
47
48
49
SiO_2
1



Na_2O
3.0
2.5
2.0
1.5
47
48
49
SiO_2
1
2
3



FeO
16
14
12
47
48
49
SiO_2
9.1
1
2
3

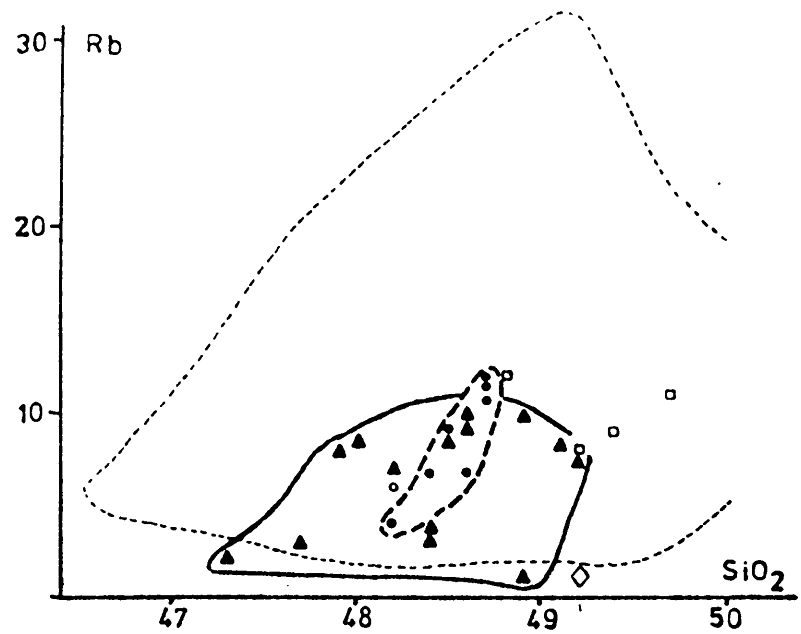


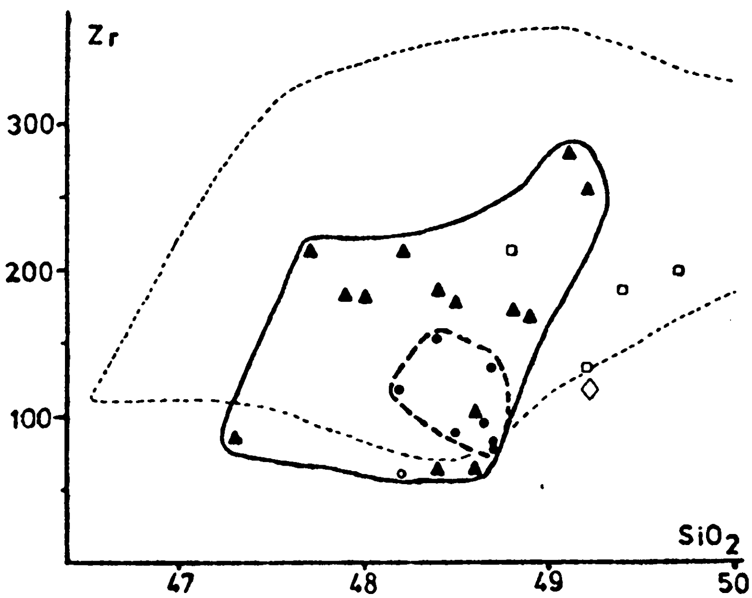
P_2O_5
0.5
0.3
0.1
47
48
49
SiO_2
1
2
3

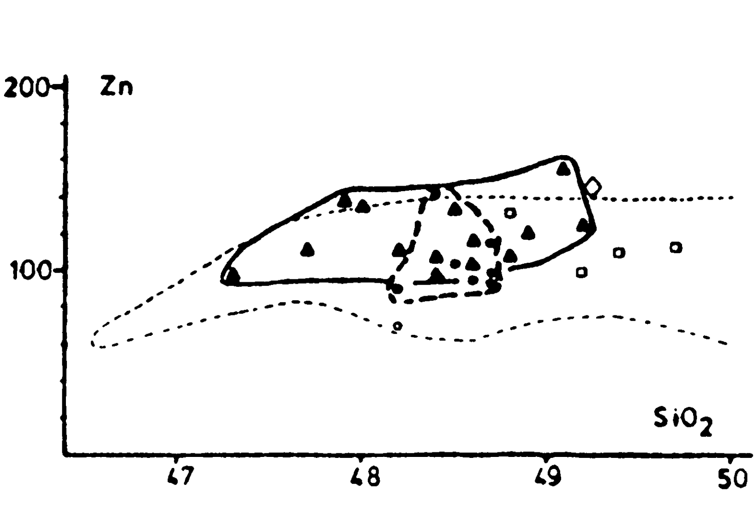
Fig.8.15

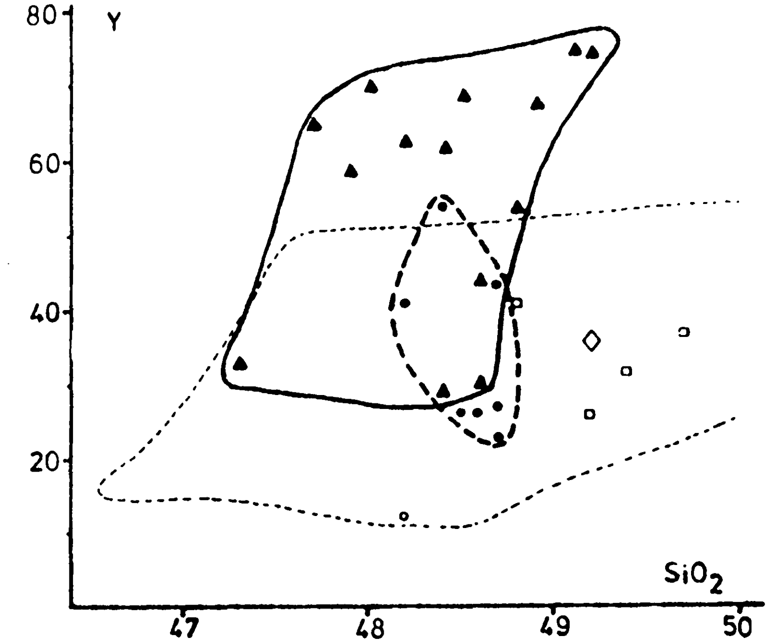
Trace elements of Skarðsheiði and Biskupstungur basalts plotted against silica.

Thin broken line	=	Compositional field of Hafnarfjall-Skarðsheiði central volcano.
Thick unbroken line	=	Compositional field of Group B
Thick broken line	=	Compositional field of Group A
Filled triangle	=	Group B lava
Filled circle	=	Group A lava
Open circle	=	Lyngdalsheiði basalt (Biskupstungur)
Open square	=	Fell Formation lava (")
Open diamond	=	Average MAR composition (Bailey and Noe-Nygaard, 1976).

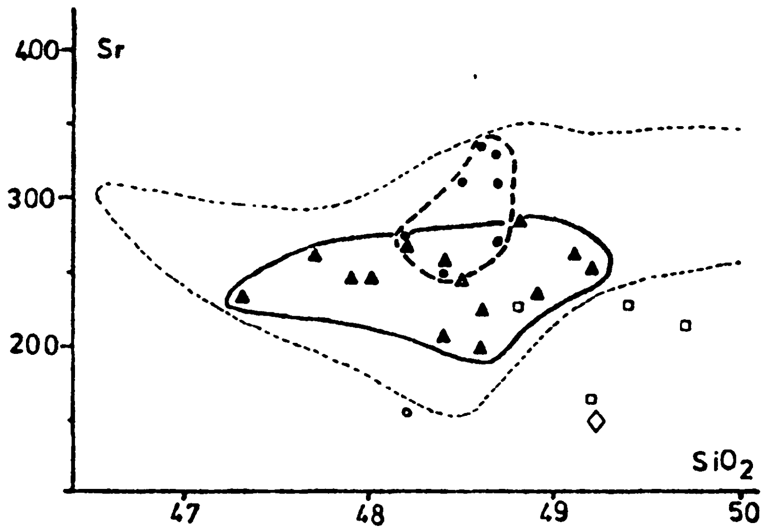

Rb
30
20
10
SiO2
47
48
49
50


Zr
300
200
100
SiO2
47
48
49
50

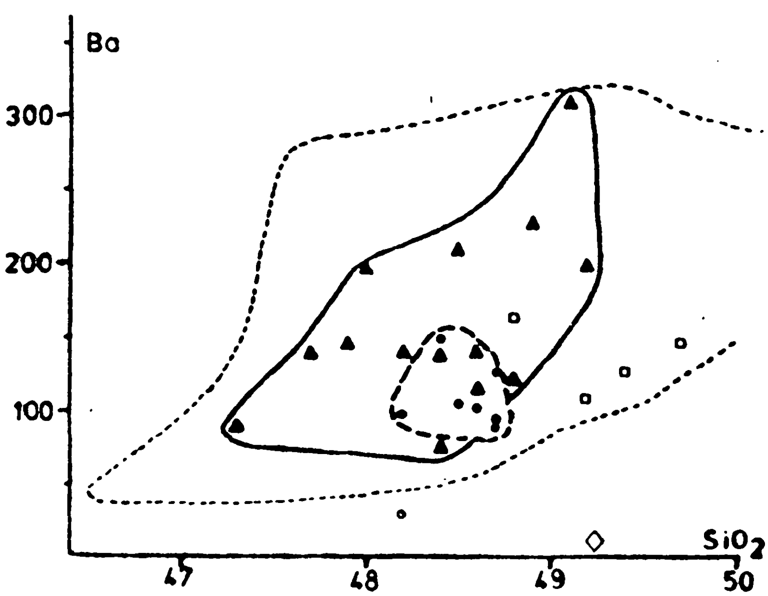

Zn
200
100
SiO2
47
48
49
50



Y
80
60
40
20
SiO2
47
48
49
50



Sr
400
300
200
SiO2
47
48
49
50



Ba
300
200
100
SiO2
47
48
49
50

Two kinds of progressive geochemical changes take place as one ascends the Group A sequence. In order to bring out these changes the group is divided into three sub-groups, i.e. A1 (H1-H5), A2 (H6-H10) and A3 (H11-H20 and S15). The boundaries of each sub-group is indicated in fig.8.14 for all the major elements except for P and Mn. The encircled numbers refer to the compositional centres of the respective sub-groups. Although the trace elements appear to respond in a similar fashion as the major elements, the limited trace element data does not allow the same sub-division of Group A in fig.8.15.

The first change is the increase in composition dispersion from sub-group A1 to A3 which is especially evident in Si,K,Al,Fe and Ti and may also be observed in Sr,Rb,Y and Zr. This is further illustrated in the plots of; K_2O v. Al_2O_3 (fig.8.16), TiO_2 v. Zr,Y v. Zr (fig.8.18,A and B), Sr v. Zr and Rb v. Zr (fig.8.17,A and B).

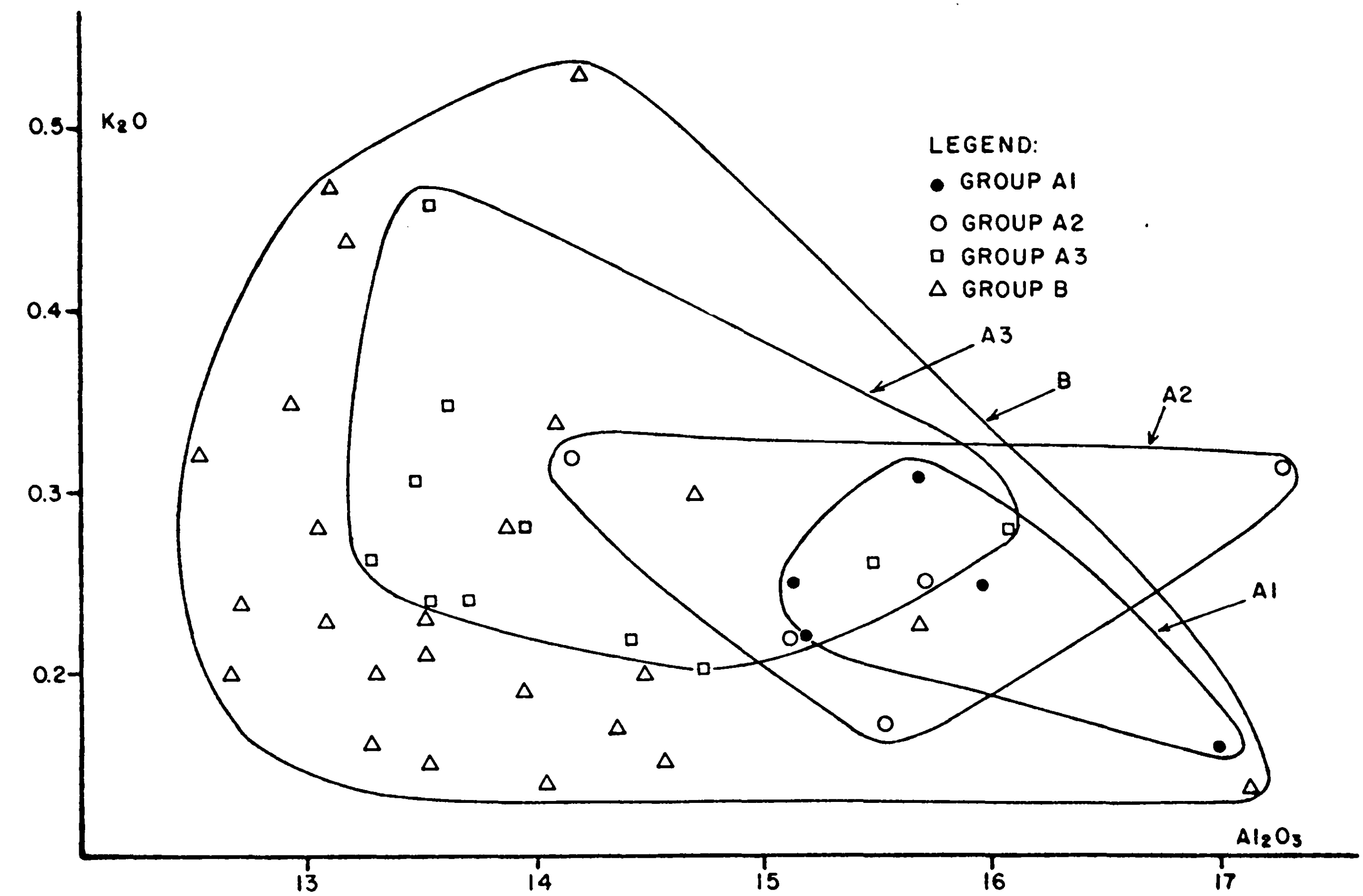
Concominant with the first change, the second change is reflected by the apparent migration of the sub-groups with time towards the compositional centre of the Group B basalts, as indicated by the encircled numbers in fig.8.14 and can further be brought out in fig.8.16.

The affinity, shown by the gradual compositional migration concominant with the increase in compositional dispersion of the sub-groups with time, towards the centre of the Group B would suggest that the latter represents an additional stage, where the compositional dispersion reaches a maximum, and thus relates to the progressive chemical changes taking place during the accumulation of the Hvalfjörður lenticular basalt unit at this location.

Plagioclase is the predominating phenocryst phase in the porphyritic lavas (H1-H13) in Heiðarhorn (Heiðarhorn Porphyritic

Fig.8.16

K of Skarðsheiði basalts plotted against Al. The compositional fields of Group B and subgroups A1, A2 and A3 are indicated.



K2O
0.5
0.4
0.3
0.2
LEGEND:
GROUP A1
GROUP A2
GROUP A3
GROUP B
A3
B
A2
A1
Al2O3
13
14
15
16
17

Fig. 8.16

Fig.8.17

Sr (A) and Rb (B) of Skarðsheiði basalts plotted against Zr.

Fig.8.18

Y (A) and TiO_2 (B) of Skarðsheiði basalts plotted against Zr.

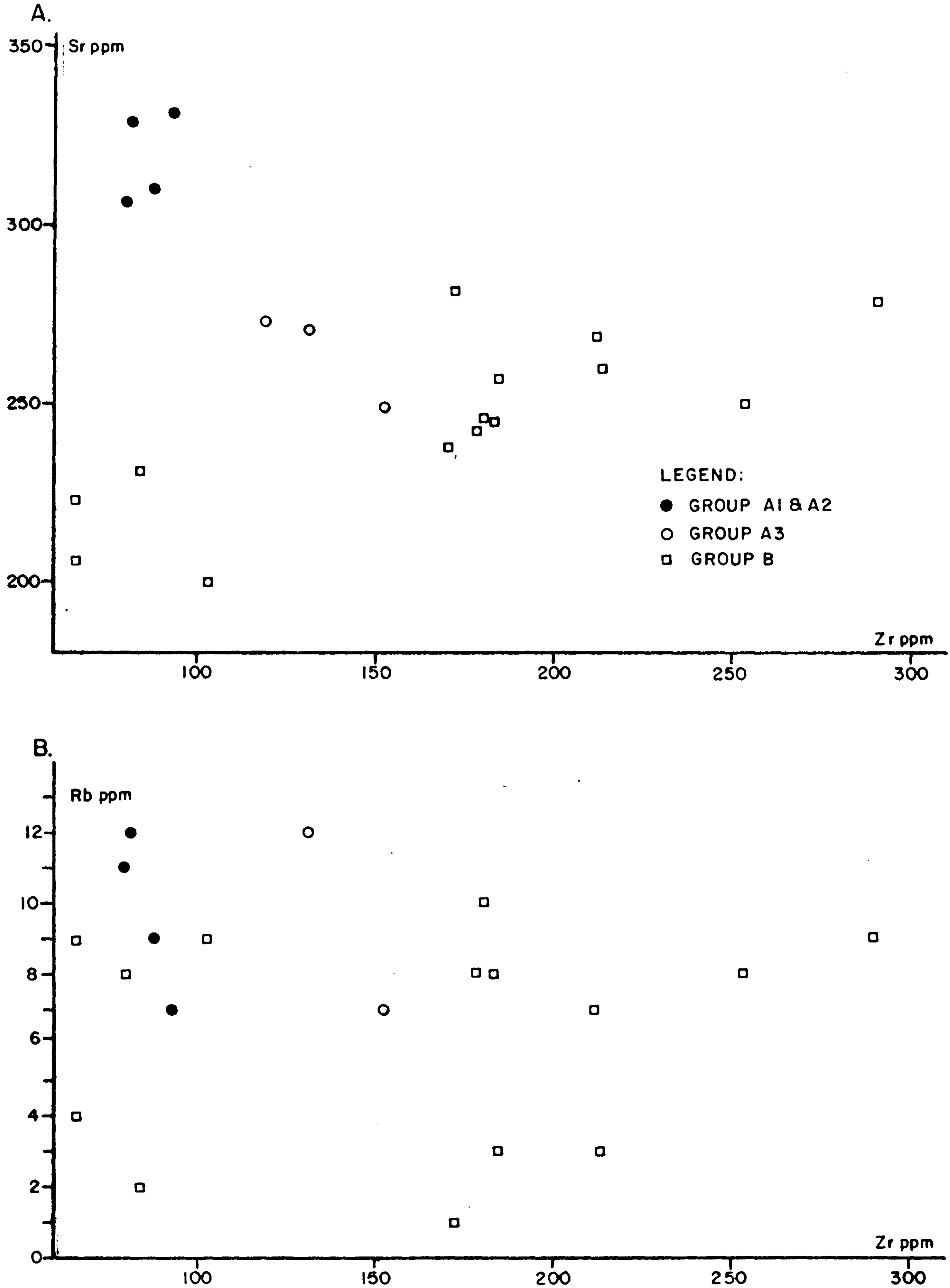

A.
Sr ppm
350
300
250
200
Zr ppm
100
150
200
250
300
LEGEND:
GROUP A1 & A2
GROUP A3
GROUP B
B.
Rb ppm
12
10
8
6
4
2
0
Zr ppm
100
150
200
250
300

Fig. 8.17

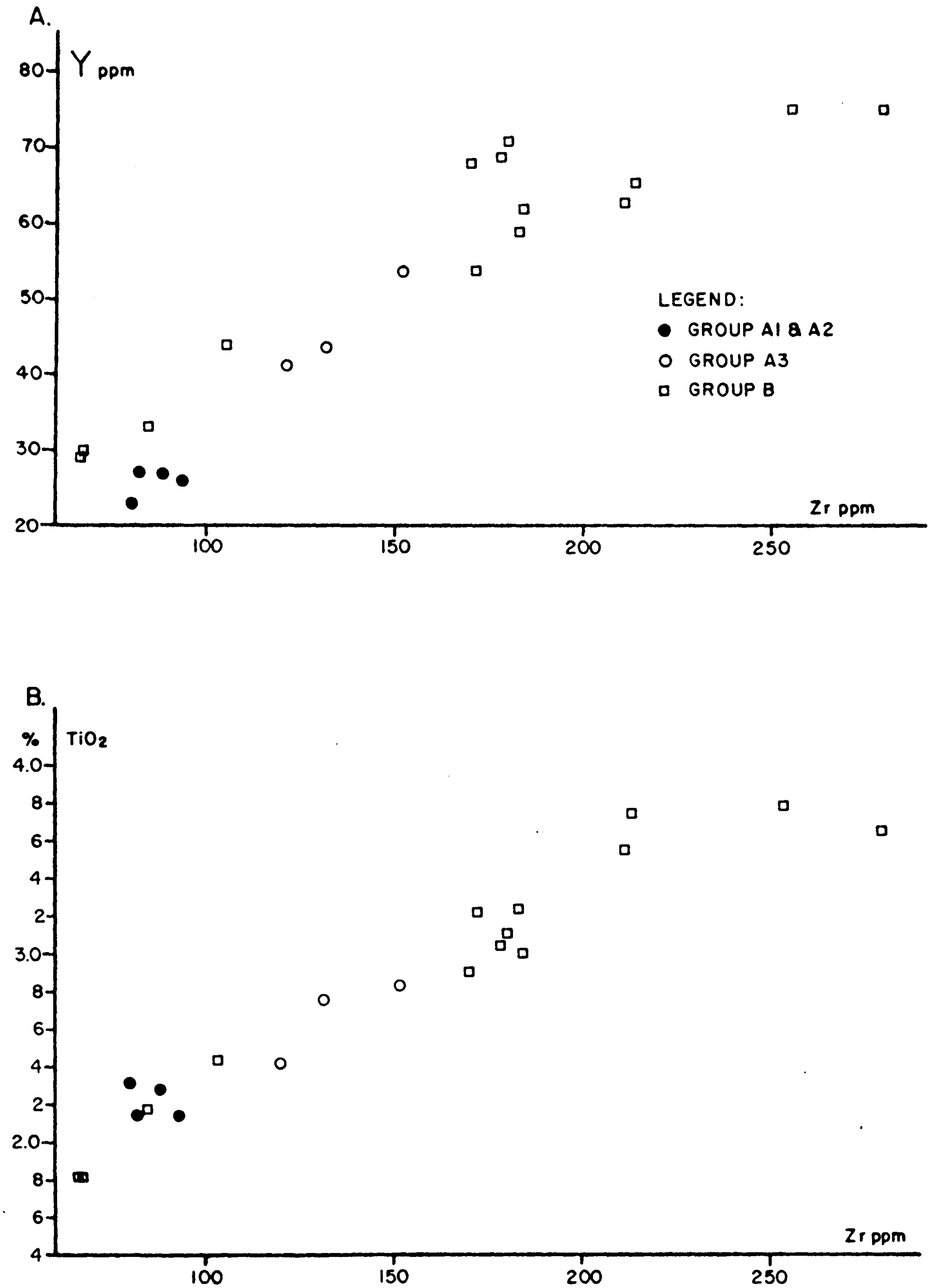

A.
Y ppm
80
70
60
50
40
30
20
Zr ppm
100
150
200
250
LEGEND:
GROUP A1 & A2
GROUP A3
GROUP B
B.
%
TiO2
4.0
8
6
4
2
3.0
8
6
4
2
2.0
8
6
4
Zr ppm
100
150
200
250

Fig. 8.18

Series, chapter 4) along with minor occurrances of olivine and rare clinopyroxene (c.f. table 8.3). The relatively high modal abundance of plagioclase phenocrysts (generally 12-18%) in these lavas is reflected geochemically by their relatively high Al and Ca (c.f. fig. 8.14) and also Sr and (less distinctly) Rb (fig.8.18,A and B). These features indicate a plagioclase fractionation with the plagioclase tending, by some process, to concentrate in the magma. The disappearance of this Al,Ca,Sr and Rb enrichment from A1 to A3 along with the disappearance of the porphyritic character of the lavas may thus reflect a diminishing plagioclase influence upon the chemical composition.

The apparent cotectic relationship of olivine and plagioclase in several of the lavas of Group A indicates that if plagioclase was fractionating, so was olivine. The Mg content within Group A goes through a progressive increase from 5-6% in A1 to 6-7% in A3. Assuming the Mg content of these magmas to be controlled by olivine fractionation, the increasing Mg content from A1 to A3 indicates a decreasing influence of the olivine fractionation. This, apparently diminishing degree of olivine and plagioclase fractionation from A1 to A3 magmas is consistent with the field data which indicates that the lava accumulation rate changed from a low value at the base of the succession to a high value towards the top (Group B).

Olivine fractionation is expected to lead to Fe-enrichment in basalt magmas. Thus if the degree of olivine fractionation is diminishing from A1 to A3 the resulting Mg increase ought to be accompanied by a decrease in Fe, assuming that these magmas evolved from a common parental magma. The opposite is, however, observed where Mg and Fe of the Group A lavas show a concominant increase from

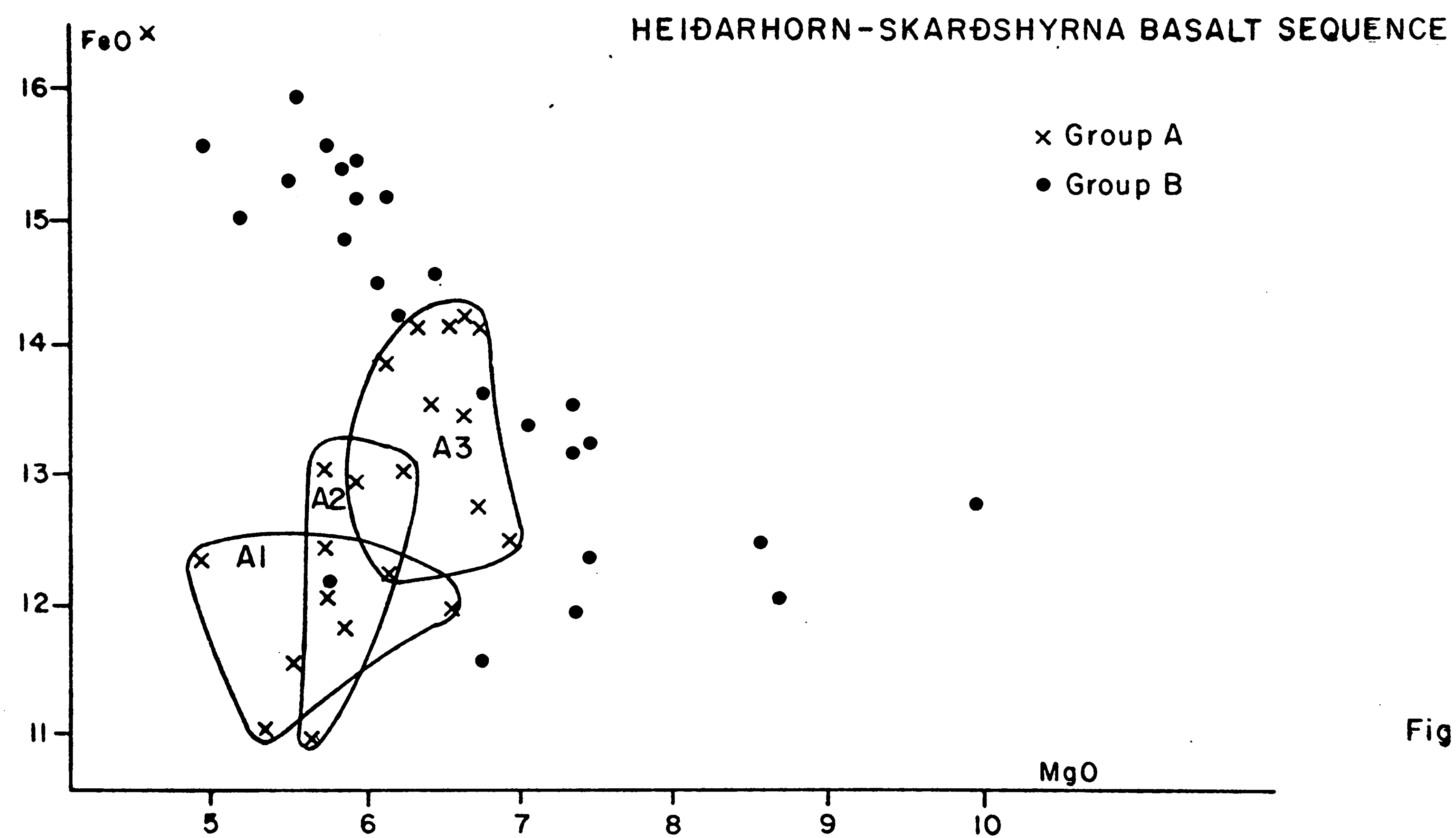

HEIÐARHORN-SKARÐSHYRNA BASALT SEQUENCE
× Group A
● Group B
FeO ×
MgO
A1
A2
A3
16
15
14
13
12
11
5
6
7
8
9
10

Fig. 8.19

A1 to A3 and where Fe increases at nearly twice the rate of Mg (resulting in a near constant F/M ratio in Group A). On a Mg vs. Fe plot (fig.8.19) the slope of Group A lies at right angle to Group B.

This problem, however, can be resolved by assuming that the olivine-plagioclase fractionation in Group A (which is diminishing with time) is a superimposed feature on parental magmas, which are themselves experiencing progressive changes with time. The parental magmas of A1 may thus have been richer in Mg (and poorer in Fe) than magmas of A3, where they probably conformed to a similar trend as exhibited by Group B in fig.8.19.

To sum up, the Heiðarhorn-Skarðshyrna basalt sequence is characterized by the following features:

1) A progressive increase in elemental dispersion.

2) A progressive migration of lava compositions towards the centre of the compositional field of Group B.

3) A progressive decrease in olivine-plagioclase fractionation in sub-groups A1 to A3 with time leading to its apparent disappearance.

4) A progressive increase in the lava accumulation rate with time.

The implications of these variables are further discussed in chapters 10 and 11.

d. The Biskupstungur basalts

The Biskupstungur district is located within the Quaternary region in southern Iceland, c.15-20 km west of the Hreppar regional anticline (fig.1.1).

Eleven samples were analyzed from this area.

The reasons for the inclusion of this analytical data is twofold;

a) Assuming a symmetrical distribution about the Reykjanes-Langjökull axial rift zone with respect to rock ages and basalt compositions, the lava sequence studied (The Fell Formation) comprises a time segment revealing basalt compositions extruded from the rift zone during early Brunhes.

b) Because of the likelyhood that the sequence accumulated within the lenticular lava unit to which the "Geysir" central volcano belongs, it is assumed to represent an analogus to the upper part of the Heiðarhorn sequence (Group B).

The analyzed samples are taken from two units of different ages:

(i) <u>Fell Formation</u>, a sequence within the Hreppar Formation (Kjartansson, 1958) of olivine-and quartz-normative tholeiite flows. The assignment of this Formation to the lower Brunhes epoch (Franzson, 1973) has recently been confirmed by K/Ar dating, giving an age of 0.58 ± 0.07 m.y. (Albertsson, 1976).

Rhyolite boulders in sediment, which probably are derived from the nearby Geysir central volcano, underlie the Fell Formation in the Gullfoss gorge, and indicate a contemporaneity of the latter with the central volcano.

The eight analyses of the Fell Formation resemble the Group B of Heiðarhorn except that they have somewhat higher Si, and lower Mg and Mn values (fig.8.14). The five samples with silica contents >49% show less compositional dispersion with respect to the major elements than those with lower silica. The limited trace-element data (4 samples, 3 of which are from the silica-rich group) suggest that the pattern of trace-element distribution may be similar to that of the major elements.

(ii) Two samples in this age group are taken from;

a) a compound lava flow from the margin of the Lyngdalsheiði compound lava shield, on the eastern edge of the Reykjanes-Langjökull rift zone and

b) from a compound lava flow (slightly plag- and cpx-phyric) overlying the Fell Formation at Gullfoss. This may have erupted within the volcanic zone east of Langjökull which is characterized by compound lava shields and relatively few fissures (c.f. Piper, 1973). Both samples may be reasonably representative of the large volume basalts, erupted during the last interglacial period.

Both contain very similar major element abundancies. In relation to the other analysed basalts (figs.8.11 and 8.14) they plot near the lower margin of the major element composition field except for Al, Ca and Mg which are high. The Gullfoss compound lava also shows low trace element abundancies. In comparison with average olivine tholeiite from Reykjanes (Jakobsson, 1972), they are lower in iron, K, Ti, P and higher in Al, Ca, Mg.

CHAPTER 9

CRUSTAL STRUCTURE OF ICELAND

On the basis of seismic refraction studies Pálmason (1971) divided the Icelandic crust into four layers. The P-wave velocities and densities for these and the immediately underlying mantle rocks are as follows:

Layer	Average P-wave velocity km/sec	Average density g/cm^3
0	2.8	2.1-2.5
1	4.2	2.6
2	5.1	2.65
3	6.5	2.9
4 (mantle)	7.2	3.1

Layer 0 is a surface layer (maximum thickness 1 km) present in the Neovolcanic zones and consists predominantly of lavas, hyaloclastites and tuffaceous sediments. The velocity difference between Layers 1 and 2 (both of which consist mainly of basalt lavas with minor sedimentary and tuff layers), is probably attributable to the progressive filling of pore spaces by secondary alteration products as well as to the increased proportion of intrusives (c.f. T. Einarsson, 1965; Friðleifsson, 1973). Pálmason's (1971) detailed map of the upper boundary of Layer 3 (nowhere exposed at the surface) shows a general depth range of 1-5 km, except in S- and N-Iceland where greater depths are recorded (max. 10 km). The thickness of Layer 3 varies from 4-6 km, except possibly in N-Iceland where it may be thicker. Pálmason noted that Layer 3 consistently lies at shallow depths beneath the extinct central volcanoes and that geomagnetic and gravity anomalies are frequently coincident with the latter. The upper boundary of Layer 4 is found at a depth range of 8-16 km.

While there is reasonable agreement among geoscientists, that Layer 3 is dominantly basaltic, opinions differ as to why its seismic velocities should be so significantly higher than those of Layer 2.

Einarsson (1965) pointed out that the Layer 3 seismic boundaries, which in many places are nearly horizontal, cut across basaltic formations which, from their surface expressions, are believed to dip at 5-10°. This, he maintained, is indicative of a metamorphic boundary. A similar view has been expressed by Pálmason (1971), who has shown that the interface between Layers 2/3 coincides with a 350-400°C isothermal surface as deduced from heat-flow measurements. Cann (1968) has argued the lower oceanic crustal layer to be within the amphibolite facies. De Wit and Stern (1976) have noted a correlation between seismic velocities in the amphibolite facies of ophiolite complexes (believed to represent elevated sections of the oceanic crust) and those in the lower oceanic layer.

A view widely held maintains, that Layer 3 under Iceland is largely composed of intrusives. Walker (1960) observed a progressive increase in dyke density with depth in E-Iceland. Gibson and Piper (1972) suggested that the Icelandic Layer 3 is predominantly composed of intrusive basaltic material. According to them, the upper boundary of this layer may reflect a zone above which relatively few magma batches ascend; the failure of magma to ascent higher may be controlled by some kind of hydrostatic equilibria. Grönvold (1972) also argued for the intrusive origin of Layer 3, and suggested that the density difference between Layer 2 and Layer 3 would favour emplacement of basaltic magmas as sheets along that boundary. According to Grönvold, basaltic magma will be added to Layer 3 allowing it to thicken and shallow until the upper surface reaches a level at which magma vesiculation can occur. With consequent decrease in density, the vesiculating magmas erupt to the surface. Similarily Walker (1974,1975) considers the ascent of magma to be a passive process dictated by intracrustal density differences. According to him the extrusion of rising magma would be favoured by high rate of delivery, large volume and low frequency of uprise. Friðleifsson (1973,1977), in his analysis on the distribution of large basaltic intrusions in Iceland and their coincidence with high elevations of the Layer 3 boundary, proposed that the Layer 2/3 boundary may in general be determined by a "metamorphic front" at which the subaerial volcanics in the crust lose their strength and thus become to accommodate large intrusives. He suggests that the relatively incoherent highly altered rocks at the Layer 2/3 interface may act more as a magma trap by virtue of their structural than their density properties.

Pálmason presents (1971, fig.5) a crustal cross-section of Iceland extending across the country from NW-SE. This section disects the research area in the south of Hafnarfjall, and shows that the Layer 3 upper boundary is slightly elevated to the west of the crest of the Borgarnes anticline. The seismic profiles upon which this cross-section is based does, however, neither include the central volcano nor the Höfn unconformity. Pronounced magnetic and positive gravity anomalies in the Hafnarfjall and Hvítá areas may be associated with still shallower depths to Layer 3. The elongation of these anomalies parallel to, and slightly to the east of, the outcrops of the Höfn unconformity, suggests that the anomalies are caused by large number of intrusives emplaced along the older crusted plate-boundary as discussed in 6.4. Field relations in the area (e.g. updoming, cone-sheets and alteration) would appear to support this suggestion (chapter 5). A possible reason for the anomalous number of intrusives along this crustal boundary may be due to the inability of the intrusive sheets, spreading along the Layer 2/3 boundary, to penetrate the older crust to the west, and to their preferential accommodation within the tectonically complex marginal zone (c.f. fig.6.5). Furthermore, the reason for the relatively high P-velocities noted in Layer 1 by Pálmason (1971) in Borgarnes (profiles 53 and 54) may be due to the Hvítá sheet-swarm, which extends into that area.

A model in which Layer 3 is of intrusive origin in the research area is compatible with most of the geological and geophysical data available. The elevation of Layer 2/3 boundary beneath central volcanoes must have primarily been controlled by the high rate of influx of magma into the crust at these locations.

In assessing the eruptive mechanism and crustal growth the following phenomena need to be taken into consideration in order to account for the anomalous magmatism within a central volcano:

1) During rifting, magma enters the crust by invitation along a fissure, as a consequence of the density difference between the crustal layers and the magma.

2) Rifting, as described by Sæmundsson (1974), occurs in distinct fissure swarms which are arranged slightly oblique with respect to the volcanic rift zone. Each swarm has the highest fissure concentration in its central area, a site which ultimately comes to be occupied by a central volcano. It has frequently been shown that after an initial lava outpouring along the entire length of a fissure, the extrusion contracts to only a fraction of its

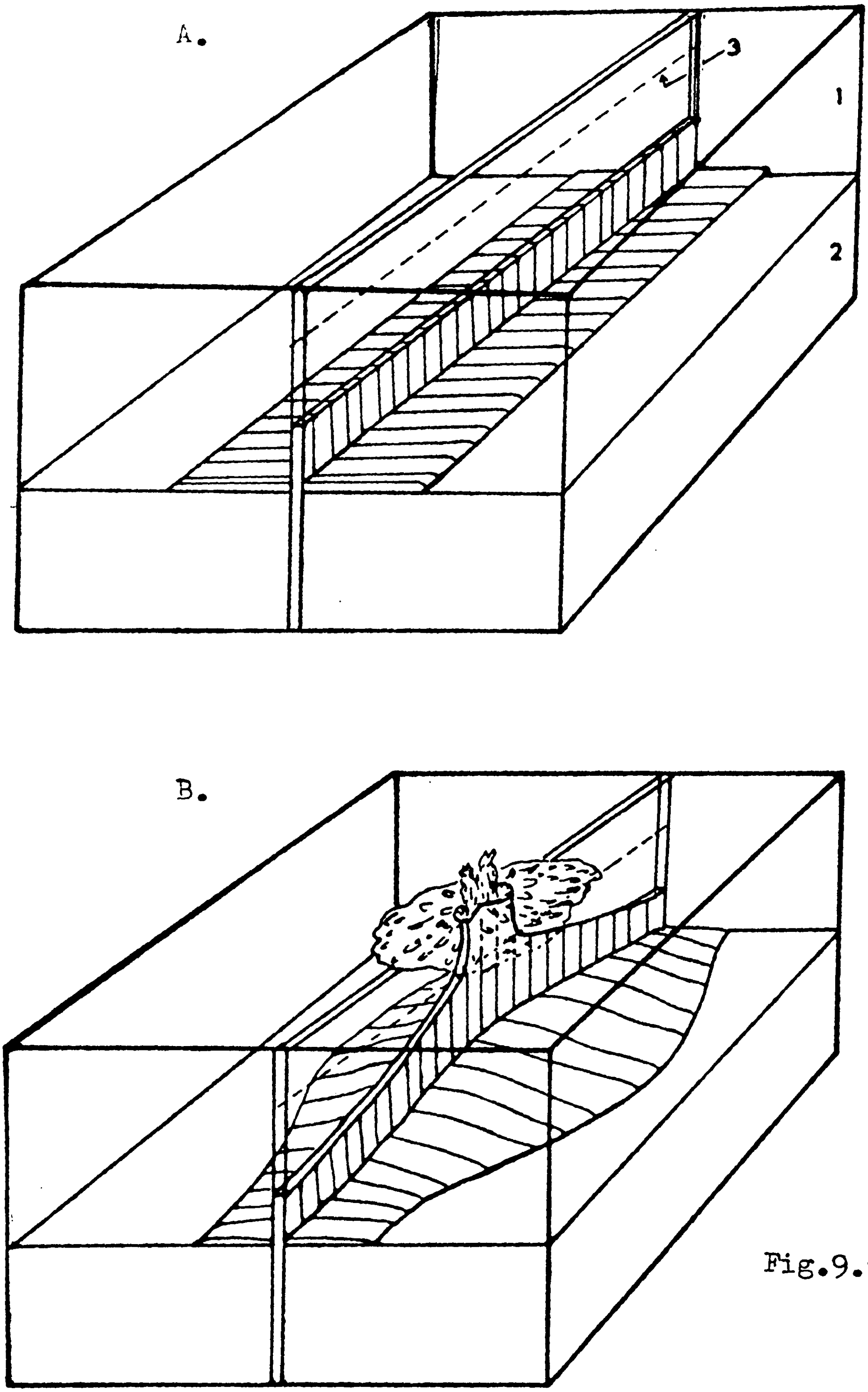


Fig.9.1

A differential volume intake of magma into crust as a result of differential Layer 3 thickness.

1. Layers 1 and 2 2. Layer 3 3. Magma vesiculation level.

original length (e.g. Th. Einarsson, 1968). Walker (1974) suggests that narrowness of a fissure may constrain the elevation of magma, because of its greater cooling surface and higher frictional energy loss per unit volume magma. Both these variables would favour a preferential volume intake of magma into the crust within the central part of the fissure swarm where there are more fissures and generally greater fissure widths.

3) A preferential thickening of Layer 3 would redirect the driving force of an incoming magma in such a way as to ensure that more volume of each magma batch will be emplaced where thickness is greatest, and that it will penetrate further into Layer 2. This is schematically shown in fig.9.1. It is worth noting in this connection that as the differential thickening of Layer 3 increases, so also does the probability, that each magma batch will ascend to where Layer 3 is thickest, increase. Thus an exponential thickening of Layer 3 with time may occur beneath central volcanoes. The two- to four-fold increase in lava extrusion rate within central volcanoes, in relation to other areas on the same fissure swarm, cannot be reconciled with an anomalously higher spreading rate alone, but is probably attributable to the higher levels generally attained by magma batches within the rifting fissures and their consequent higher extrusion rates.

The relationship between calderas, cone-sheet swarms, dykes and the Layer 3 elevation in the research area are discussed in 3.4, 5.2, and above.

It is proposed here that sagging features, calderas and cone-sheet swarms, are causally related to the anomalously thick and elevated Layer 3 beneath central volcanoes.

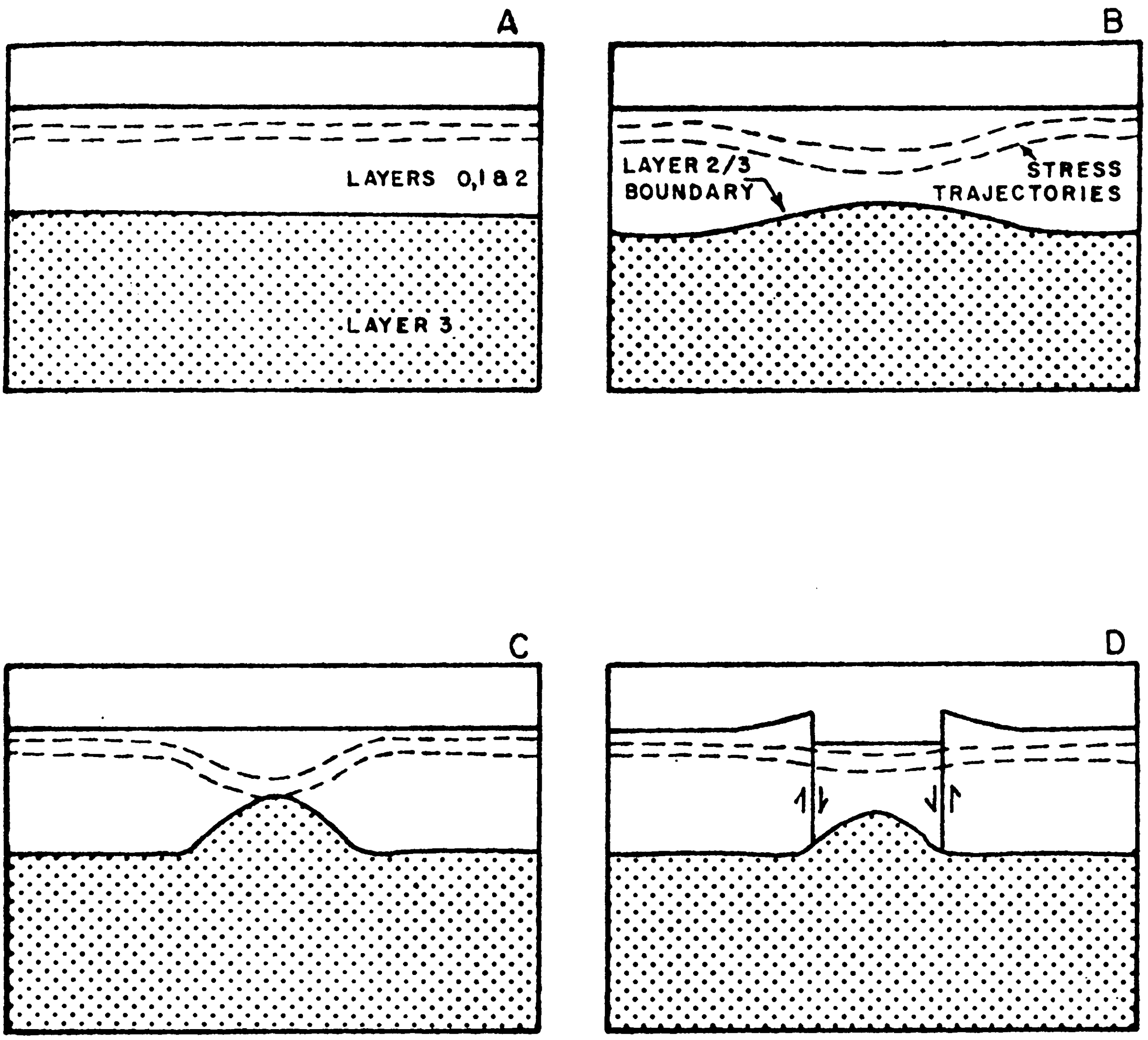


Fig.9.2

A schematic illustration of the gradual elevation of Layer 3 leading to a caldera formation; see text for further explanation.

The effect on the upper crust (Layers 0.1 and 2), by the upward migration of the higher density Layer 3 at the expense of Layer 2 (see above), is schematically illustrated in fig.9.2 and discussed below:

The progressive elevation as well as the concominant narrowing of the Layer 3 bulge shown in A,B and C concentrates the stress along a localized crustal sector, which eventually leads to rupture (D). An increased inclination of strata towards the highest elevation of Layer 3 in the core of central volcanoes is a well known feature in deeply eroded Tertiary regions. In addition, Walker (1975) noted a correlation between the degree of sagging and the concentration of sheets in SE-Iceland. It is of interest to note that the western margins of the Hróar and Hrossatungur basins (see 3.4) adjoin the eastern margin of the Ölver-Hvítá flexure.

The stress release associated with the initial caldera fracturing is likely to depend partly on the elastic strain within the upper crust at the time of fracturing. The elastic strain factor would encourage a larger amount of subsidence and might, furthermore, result in uparching of the area adjacent to the caldera (fig.9.2,D). A correlative lowering of the Layer 2/3 boundary below the caldera would be expected.

Evidence in the research area would tend to corroborate this concept. Thus, the great thickness ($<$ 300 m) of the lower basalt breccia unit (2) flooring the Hafnarfjall caldera would point to a relatively large initial subsidence. Lavas northeast of the caldera, show a notable thinning during the episode of caldera subsidence (average lava thickness 2.3 m) in comparison to the earlier and later lavas (3.2 m and 3.3 m respectively). This would

Fig.9.3

A. A widening of the outer perimeter during crustal dilation.

B. Three possible magma injection routes into the upper crust, i.e. by
   (i) a horizontal sheet,
   (ii) a cone sheet and by
   (iii) a dyke.

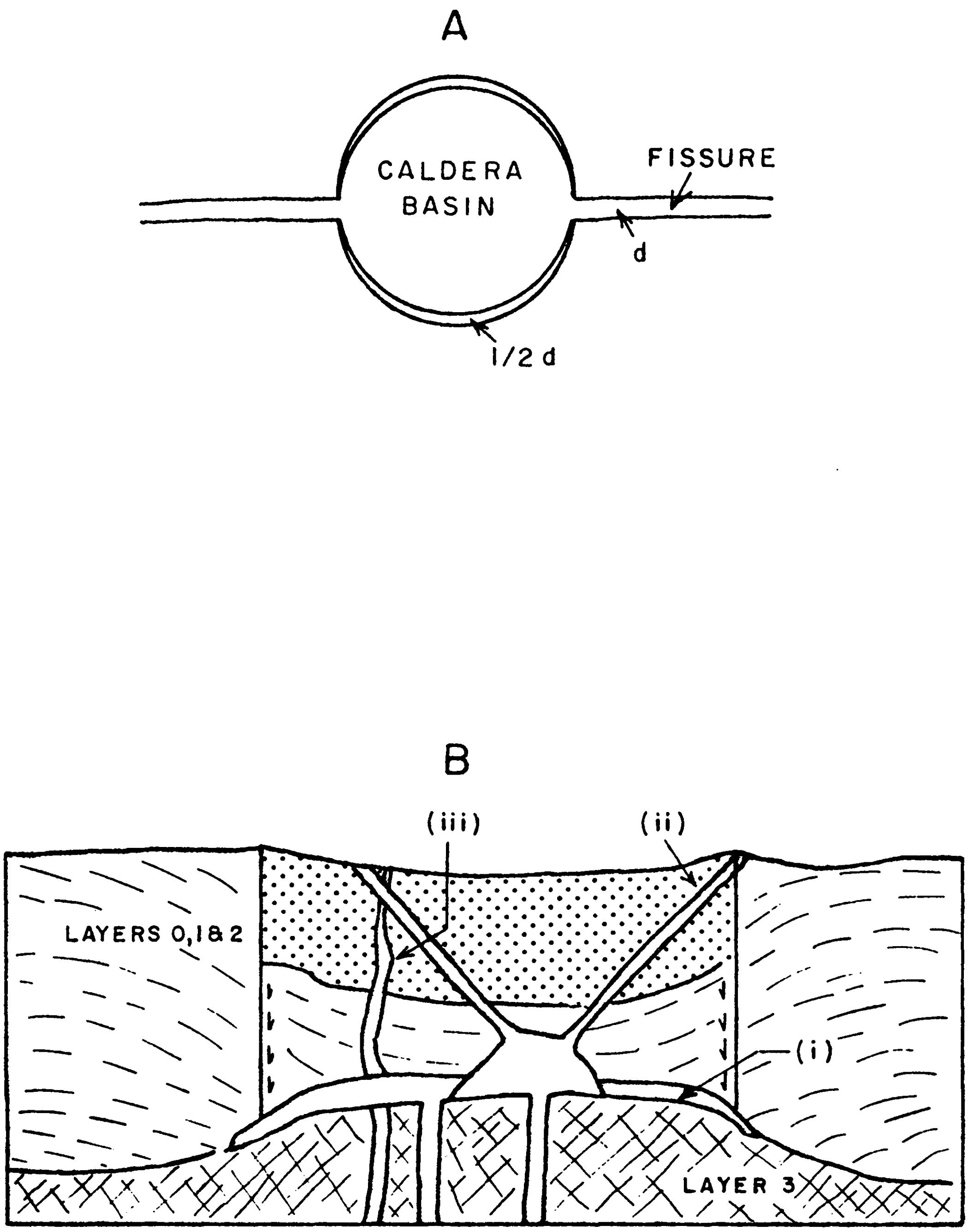


Fig. 9.3

conform to an increase in deposition slope.

Following upon the formation of the initial fracture, any subsequent rifting disecting the central volcano would proceed as before, or be relieved by the caldera fracture and thus encourage a subsidence of the caldera floor (fig.9.3,A). Thus it is conceivable that the decoupling of the caldera floor from normal rifting procedure would create a barrier for magma upwelling near the Layer 2/3 boundary. There, as illustrated in fig.9.3,B, the magma may form a sub-horizontal sheet, or form a cone-sheet following the stress trajectories set by an inflationary magma body, or alternatively intrude the fractured caldera floor. Such additions to the caldera block would result in a gradual subsidence. There is ample evidence for such a gradual subsidence in the Hafnarfjall caldera, where the rate is believed to be comparable to that of the Þingvellir graben. The frequent occurrence of lavas interleaving the breccia units in the Hafnarfjall caldera indicates that during much of this episode, the caldera remained a mere shallow depression perhaps similar to the modern Krafla caldera in NE-Iceland.

In contrast with the Hafnarfjall caldera, which conforms closely to the norm caldera for other central volcanoes, the Brekkufjall caldera is atypical for the following reasons: a) The subsidence is believed to have occurred as a one stage event. b) This event closely relates to the intense, large-volume and differentiated extrusions, which antedated, accompanied and postdated the collapse. c) The highly xenolithic nature of most of the extrusives. d) The absence of cone-sheets .

It is suggested here, that the caldera originated through the upward migration of a large volume of magma, perhaps by stoping, which resulted in the copious extrusion and roof-collapse when it reached high levels.

CHAPTER 10

THE RELATIONSHIP BETWEEN TYPES OF BASALT AND LAVA EXTRUSION RATE

As illustrated in the previous chapter, rifting along the axial zones in Iceland gives rise to distinct fissure-swarms associated with dyke-swarms and lenticular lava units.

The following account attempts to relate variations in basalt compositions with episodes of contrasting extrusion rates during the growth of such lenticular lava units, i.e. during episodes of a) low extrusion rate and b) high extrusion rate.

This relation will be discussed first in terms of field observations and secondly in terms of geochemistry.

10.1 Field geology

a. Basalts extruded during episodes of low extrusion rate

Such basalts are exemplified in the Hvalfjörður lenticular unit by the Heiðarhorn Porphyritic Series (chapter 4). After a long period of dormancy (c. 0.2 m.y.), fissure eruptions commenced and built up a lava series of great lateral extent. The focus of activity, where the basalt series is thickest, ultimately became the site of the Hvalfjörður central volcano. The large proportion of sediment in the lower part of the series suggests that, at first, eruptive rates were low.

The Hafnarfjall Olivine Tholeiite Series (chapter 3) forms the base of the Hafnarfjall-Skarðsheiði lenticular lava unit. Some atypical tectonic conditions in the research area makes it difficult to assess the extrusion rate during its accumulation (i.e. it overlies a relatively rigid old basement (c.f. chapter 6)).

However, geological mapping northeast of the area (Jóhannesson, pers. comm.) gives reason to believe that the series accumulated during an episode of low extrusion rate.

In addition they are to be found at other stratigraphic levels where episodes of low extrusion rate are indicated. This can be indicated by the Leirárvogur Porphyritic and Olivine Tholeiite Series accumulated during the relatively quiescent interval between Brekkufjall and Hafnarfjall phases. The contemporal basalt sequence north of the central volcano is sediment-rich and does contain similar lava types (Jóhannesson, 1975). Similarily, the appearance of the Reinir compound lava shields after the demise of the central volcano, may indicate a return to a low extrusion rate in the area.

The accumulation of porphyritic and/or olivine tholeiite series during episodes of low extrusion rate is also evidenced in other areas.

Thus the low extrusion rate at the onset of rifting in the upper Borgarfjörður region is characterized by porphyritic lavas with intercalated sediments (Hreðavatn Series) underlying the Hallarmúli acid rocks (Jóhannesson, 1975; McDougall et al., 1977).

The same authors also report the existence of a sediment-rich porphyritic series during late Epoch 5 (c.5.3-5.8 m.y.) in the upper Borgarfjörður region, which accumulated at a time of low productivity in the Reykjadalur central volcano.

Several distinct porphyritic series have been mapped in eastern Iceland (Walker, 1959, 1963, 1964; Gibson et al., 1966). While the fissure swarms associated with these are generally not identified, the Fossárvík Porphyritic Group (Blake, 1970) may have been erupted from the fissure swarm associated with the Lón central volcano.

The Fossárvík Group is overlain by a sequence of tholeiite lavas (with very variable flow thicknesses) probably erupted from the same fissure-swarm. Thus, the Fossárvík Porphyritic Group may well be analogous to the Heiðarhorn Porphyritic Series at the base of the Hvalfjörður lenticular lava unit.

The predominance of olivine-phyric lavas in the condensed lava sequences towards the edges of lenticular lava units (Wood, 1976; Wood et al.,1976) may also be viewed as an indication of the confinement of this lava type to episodes of low extrusion rate.

b. Basalt erupted during high extrusion rate

These basalts are exemplified by those extruded within the active central volcano (i.e. Hafnarfjall-Skarðsheiði). They differ in two characteristics from those erupted during episodes of low extrusion rate:

1) They are extruded at twice and in some cases up to six times the rate of those of the contemporaneous flood basalts (this difference is greater when compared with episodes of low lava extrusion rate. Individual lavas, however, are likely to represent smaller magma volumes.

2) The thin central volcanic basalts are predominantly aphyric or contain one (micro)phenocryst species, while the lavas of the other type commonly contain two or more phenocryst phases.

Similar features are also evident from other central volcanoes of the axial rift zones (see e.g. Friðleifsson, 1973; Jóhannesson, 1975).

10.2 Geochemistry

It was argued earlier (chapter 8) that two kinds of progressive chemical changes occurred concominantly with the "gradual" transition from low to high extrusion rate in the Hvalfjörður lenticular lava unit, i.e. 1) an overall enrichment in most incompatible elements as well as an increase in compositional dispersion of the lavas, and 2) an episode of "low-pressure" olivine and plagioclase fractionation, most pronounced at the base of the sequence (sub-group A1) but gradually diminishing upwards and terminating, along with the porphyritic character of the lavas, towards the upper part of Group A. It is likely that the Heiðarhorn Porphyritic Series evolved from olivine tholeiitic parental magmas, i.e. relatively rich in Mg but low and monotonous incompatible element abundancies. The apparent similarities to other porphyritic series with respect to phenocryst phases and the accumulation of these lavas during episodes of low extrusion rate, leads to the suggestion that they have experienced low-pressure fractionation.

The evidence above of the low LIL-element abundancies in porphyritic lavas is supported by Sigvaldason´s and Steinþórsson´s (1974) argument that large-volume porphyritic lavas and compound lava shields are the most depleted rocks in Iceland. In addition Wood (1976) and Wood et al. (1976) have reported that olivine-phyric lavas in eastern Iceland have low Zr and low La/Sm ratios.

In contrast to the relatively uniform and LIL-depleted content of the magmas which in general are associated with the low extrusion rate episodes, the magmas of the Hafnarfjall-Skarðsheiði central volcano show a wide compositional range, extending towards basaltic andesites (low-Al group) with high Fe,Ti,K and Na and concominantly low Mg, Ca and Al values. A correlation between variations of composition with time could not be attempted within the volcano due to incomplete sampling. However, the Group B of Heiðarhorn sequences and the Fell Formation in Biskupstungur, both contemporaneous with central volcanic activity, demonstrate that lavas, at a vigorous stage in the built-up of a lenticular lava unit, do exhibit a large compositional dispersion with no apparent inter-relationships.

It is noteworthy that although the central volcanoes do show a predominance of lavas with moderate contents of incompatible elements, LIL-depleted lavas also occur, from which it may be inferred that the eruption frequency of the latter may remain constant throughout the lifetime of the lenticular lava unit although the extrusive products may be less conspicuous because of their becoming intercalated with large quantities of more LIL-rich products in such environments.

The wide compositional field of basalts reported from other Icelandic central volcanoes of Þingmúli type is similar to that found in the research area (e.g. Carmichael, 1964; Sigurðsson, 1970; Grönvold, 1972; Friðleifsson, 1973; Sigvaldason and Steinþórsson, 1974; Jóhannesson, 1975).

Recently Jóhannesson (1975) showed for the Reykjanes-Langjökull rift-zone a progressive shift in composition for the lavas during the past 5 m.y. No such secular variation can be observed in the three lenticular lava units from this same rift zone covered by this study, (Hafnarfjall-Skarðsheiði (5.5-4 m.y.), Hvalfjörður (c.4-3 m.y.) and "Geysir" (c. 0.5 m.y.) units).

However, if it can be shown that a progressive shift in the bulk of the basalts analysed of individual lenticular lava units occurred through time towards the relatively primitive compositional field of Recent extrusives of the Reykjanes-Langjökull rift zone, only then can such changes be verified. The author considers it more likely that if such changes occurred (or are still occurring), they may be associated with a gradual fall off in rifting velocity of the Reykjanes-Langjökull rift zone, brought on by the southward transgression since early Matuyama times of the eastern volcanic zone and its increasing participation in the rifting process.

The following conclusions may be drawn from the above discussion:

1) It has been shown that, during episodes of low extrusion rate in the research area and at least in some other regions in Iceland, porphyritic and/or olivine tholeiite lava series (compound lava shields) are preferentially erupted.

The porphyritic nature of many of these lavas is likely to be attributable to low-pressure fractionation episodes.

The lavas tend to be relatively voluminous and to exhibit a predominance of primitive and monotonous LIL-element abundancies.

2) In contrast, lavas accumulated during high extrusion rate display a large compositional dispersion. They are generally richer in LIL-elements and are also believed to represent smaller volumes than the other type.

3) Where a progressive increase from a low to a high extrusion rate has taken place, such as occurred during the accumulation of the Hvalfjörður lenticular lava unit in Skarðsheiði, such changes are reflected in chemistry by a concominant increase in compositional dispersion, an overall enrichment in LIL-elements and a phasing out of low-pressure fractional crystallization.

4) The chemical composition shows an apparent covariance with the rate of extrusion (which, in turn, is directly related to

the rate of rifting and the crustal structure (c.f. chapter 9)). This is brought out where a change from a high to a low extrusion rate results in the (re)appearance of basalts of relatively primitive and monotonous compositions.

CHAPTER 11

PETROGENESIS

11.1 Basalt genesis

Uncertainities regarding the nature of, and the conditions in, the mantle and the processes affecting the basaltic magma batches once they have been generated and make their way to the surface, have given rise to numerous hypotheses concerning the generation of basaltic compositions as seen in lavas and shallow intrusives.

Many of the salient features of such hypotheses are embodied in the models propounded by O'Hara (1968) and Green and Ringwood (1967).

The latter authors (and Green, 1971) advocate that primary magmas can be generated through partial melting during diapiric and adiabatic uprising of mantle material, where the magma composition would largely be controlled by the depth and degree of partial melting and the phase assemblage in the source rock. They argue that in one sense fractional melting may be regarded as the reverse of fractional crystallization, providing that the nature of the crystalline phases is similar in both cases. This relationship would be independent of the actual proportions of phases which may be present. They propose that the magma segregation generally involved a partial melting of between 20-40%, and also suggests that quartz normative tholeiites can be generated at depths of less than 5 kb (c.15 km) by lower degrees of partial melting.

O'Hara, however, has laid stress on the likelihood that basaltic magmas, once they have been generated by partial fusion, will be subject to crystal fractionation at all levels during ascent, and that the great majority of basalts erupted at or near the surface will have been more or less profoundly modified by fractionation processes. In particular, he suggests that the cotectic character ($\geq$ 2 phenocryst phases) of the oceanic tholeiites (MORB), along with their restricted composition field, are indicative of such modification, and cannot therefore represent primary magmas.

However, the former postulation (Green and Ringwood, 1967) has found an acceptance among trace elements geochemists such as Gast (1968), Kay et al.(1970), and Schilling (1973a, 1973b) who have tended to regard the effects of crystal fractionation as of slight importance.

Gast (1968) and Kay et al. (1970) argue that the characteristics of "MORB" are acquired principally during large scale melting events (20-40%) at depths of 15-25 km.

Schilling (1973a, 1973b), taking note of the contrast between the LIL-depleted MORB basalts dredged from the Reykjanes Ridge and the, in general, much more LIL-enriched basalts of Iceland, as well as the distinctions in $^{87}Sr/^{86}Sr$ and REE- patterns in the two environments, proposed that the Icelandic and MORB basalts to the south, were derived from two wholly independent mantle sources. The MORB, he supposed, derived from shallow-level large scale melting of hitherto LIL-depleted oceanic upper mantle, while the basalts of the islands derived from the adiabatic melting of upwelling "plumes" of relatively LIL-enriched source rock arising from deep levels in the mantle. The mixing of basaltic products from the two domains is believed to have resulted in the basalts showing "intermediate characteristics" between typical MORB and typical Icelandic type, found along the 400 km of the Reykjanes Ridge immediately SW of the

Reykjanes peninsula.

While this "two source" hypothesis with or without modification, has received some popularity, it has not been without criticism. Thus, O´Hara (1973) has attempted to show that the two contrasted basaltic types could conceivably be related by crystal fractionation, with the primary magmas being derived from a single mantle source. He argues, that many of the differences in major and minor element (including REE) distribution patterns between the MORB and the Icelandic basalts could be explained in terms of the increasing outflow of magmas towards Iceland. Consequently the Icelandic magmas may be assumed to have risen through a thicker superstructure and to have taken much longer periods to ascent from source to eruptive site. The slow ascent would in turn have allowed greater scope for polybaric fractionation. Thus, the relative enrichment of incompatible elements implies that those basalts erupted at the highest levels (on Iceland itself) represent residual liquids after crystallization of at least 75% of the primary magma. However, O´Hara´s hypothesis is more difficult to sustain when the isotopic differences are considered.

Flower et al. (1975) also propose a single (homogeneous) mantle source for the island and submarine-ridge basalts. Their model depends upon the degree to which mantle-phlogopite broke down and became incorporated in the primary magmas. In this model phlogopite plays a critical role when it comes to the determination of the content of LIL-elements and the $^{87}Sr/^{86}Sr$ ratio in the primary melt. This explanation followed upon the attempt by O´Nions and Pankhurst (1973) to explain the $^{87}Sr/^{86}Sr$ differences in terms of the partial melting of a homogeneous mantle source in which the component minerals displayed isotopic disequilibrium. However, in a later paper O'Nions et al. (1976) conceded that it was more likely that a heterogeneous mantle source was involved and further stressed, that the isotopic data did not suffice to give any indications of the relative depth(s) of these different mantle sources. Furthermore, Hofman and Hart (1975) presented a strong case against the possibility of isotopic disequilibria being maintained over short distances (i.e. grain to grain) under mantle conditions but emphasized the probability that the mantle source possesses marked large-scale heterogeneity.

While the trace element geochemists readily concede that fractional crystallization may modify the composition of basalt magma on its way to the surface, they maintain that fractionation alone is unlikely to be able to account for the relative enrichment of the incompatible elements without conferring a non-basaltic composition to the magma.

However, O'Hara (1977) has shown that high trace element concentration may be achieved while maintaining an overall basaltic chemistry by fractionation operating in an "open-system" volcanic model. In this, basalt magmas are derived from near surface magma chambers undergoing continuous two (or more)- phase fractional crystallization. The chamber is regularly fed with batches of parental magmas (resulting in magma escape at top) which in turn mixes with the liquid remaining. This leads to an inevitable enrichment of incompatible elements and can furthermore explain significant variations in the ratios of incompatible elements. O'Hara does, however, concede that, only if the model of volcanic plumbing can specifically be excluded, can the incompatible elements enrichment in basalts be used in support of their primary nature.

The state of the mantle beneath Iceland has mainly been deduced from geophysical evidence; heat flow measurements (Pálmason, 1971; 1973) and magnetotelluric data (Hermance and Grillot, 1974), indicate that magmatic temperatures of basalt are reached near the Layer 3/4 boundary (Moho). Bott (1965) argued that the evidence of anomalously low mantle density beneath Iceland (obtained from gravity and seismic data) is consistent with the mantle having undergone over 10% partial fusion to the depth range of 150 km. The geophysical evidence does, however, appear to be inconclusive, as far as it does not favour either of the two petrogenetic models for basalt generation (primary basalts versus fractionated basalts).

In the preceding chapter, an argument was put forward, that basalt compositions in Iceland can to some extent be correlated with the tectonic environment in which they appear. Thus, during episodes of low extrusion rate, magmas with an overall primitive, as well as monotonous compositions predominate (but variable MgO content), whereas during episodes of high extrusion rate the magmas show larger compositional dispersion extending into more evolved basalt compositions.

The geochemical evidence from the Heiðarhorn Porphyritic Series (products of a low extrusive episode) is indicative of olivine depletion and plagioclase enrichment leading in some cases to slightly quartz normative compositions with relatively high Al, Ca, Sr and Rb values. These lavas do, however, retain relatively low and uniform incompatible element abundancies. These geochemical indications are supported by the petrography, as these lavas contain abundant plagioclase phenocrysts and only rare phenocrysts of olivine and augite (c.f. table 8.3). According to O'Hara's argument (c.f. 1973) the cotectic relationship of the lavas should strongly indicate that these magmas had equilibrated by fractionation to low-pressure environment.

A comprehensive petrological study of the two westernmost fissure swarms on Reykjanes Peninsula (Jakobsson et al., in press) revealed a succession of lavas (spanning the last c. 12.000 yrs) from early picrite (oceanite) through olivine tholeiite to latest tholeiite compositions. Beside the relatively smooth chemical trends and the steady rise of the FeO/MgO ratio with time, the lavas predominantly contain 3 phenocryst species (i.e. any combination of the following; chromite, olivine, plagioclase, augite) demonstrating the low-pressure cotectic control (fractional crystallization) of the chemical compositions.

However, most lavas analysed from the Reykjanes Peninsula (Sigvaldason and Steinþórsson, 1974; Jóhannesson, 1975) show low and constant incompatible element abundancies relative to other Icelandic basalts. Comparison, however, of the available data on basalts erupted during episodes of relatively low extrusion rate, with basalts of MORB type (lavas on Reykjanes peninsula included) does indicate similarity in their evolution, i.e. low pressure cotectic fractional crystallization prior to eruption, which, however, has led to little enrichment in LIL elements.

Several lines of evidence do limit the applicability of the model of high level (open- as well as closed-system) fractional crystallization to the basalt magmas extruded during episodes of high extrusion rate:

1) The positive correlation between high extrusion rate and compositional dispersion (towards more evolved compositions) clearly conflict with O´Hara´s (1973) contention that increasing the eruption rate should lead to extrusion of more primitive magma (as would be expected if the degree of fractionation is proportional to time).

2) Fractionation at shallow crustal level(s), implicit in O´Hara´s (1977) model, should lead to notable porphyritic extrusives with two or more phenocryst species. The opposite has been observed within the central volcano under consideration, where aphyric lavas predominate. Furthermore, cone-sheets, which are likely manifestations of the existence of small (inflationary) magma chambers at 2-4 km depth range where the rise of magma was interrupted on its way to the surface, are similarily predominantly aphyric. It is possible therefore that these magmas may be relatively primitive with eruptive temperatures above that of the low pressure cotectic. However, this clearly remains to be tested experimentally.

A comparison between numbers of (micro)phenocryst species and the normative groups of olivine tholeiites and quartz tholeiites in the research area is shown in fig.11.1,B. A similar compilation (fig.11.1,A) was attempted from the regions of Kerlingarfjöll (Grönvold, 1972), Esja (Friðleifsson, 1973) and upper Borgarfjörður (Jóhannesson, 1975). It is noteworthy that within the areas concerned a larger proportion of the olivine tholeiites (c.40-50%) contain two or more (micro)phenocryst phases than do quartz tholeiites (c.25-30%). This is the reverse trend of what would be expected if both groups had evolved from similar parental magmas by fractional crystallization.

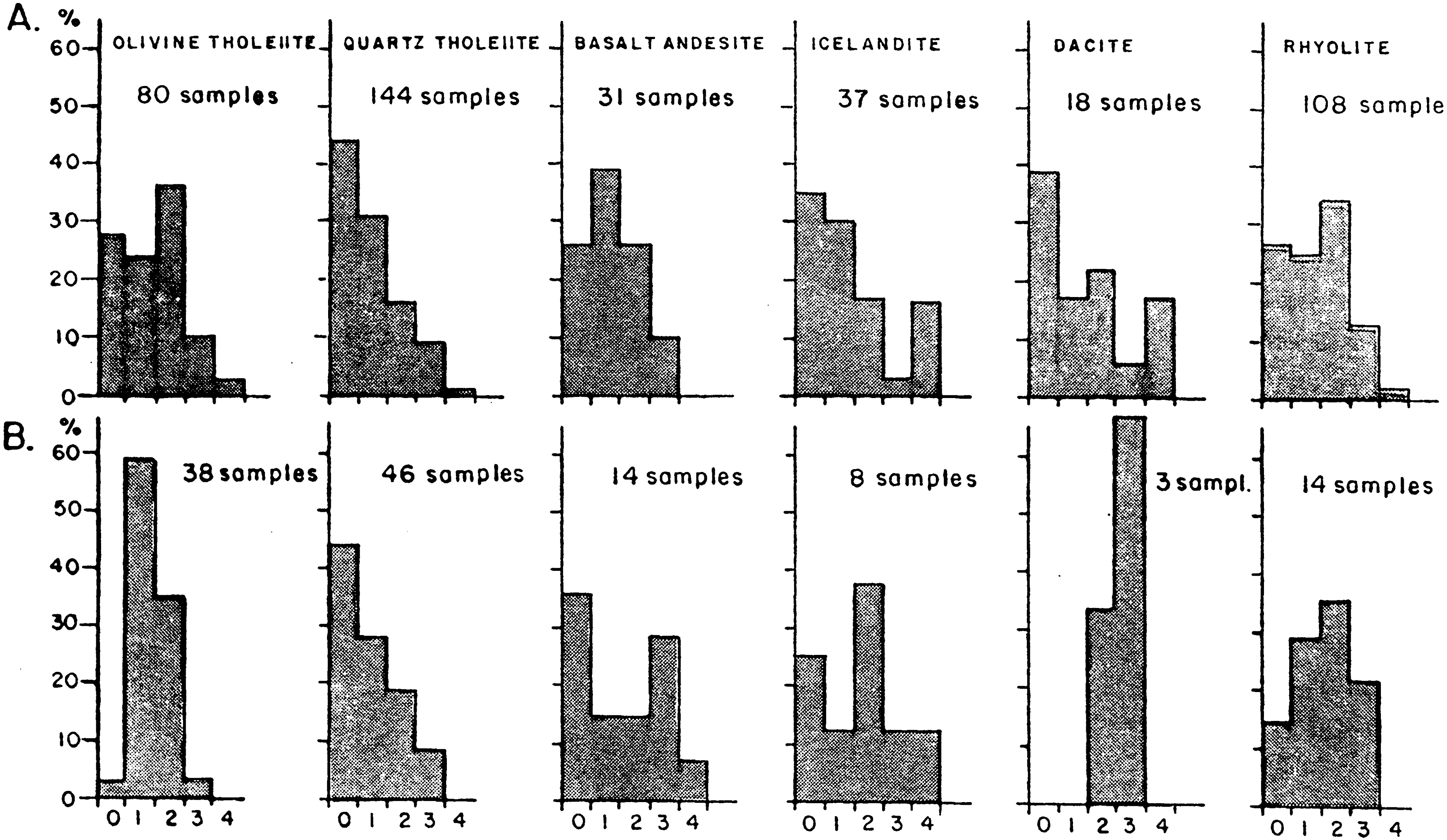
Fig.11.1

Histograms exhibiting the number of (micro)phenocryst phases (horizontal axis) plotted against their abundance (%) (vertical axis)

A. Histograms deduced from petrological data of Grönvold (1972), Friðleifsson (1973) and Jóhannesson (1975)

B. Present study

Fig. II.1


A.
%
60
50
40
30
20
10
0
OLIVINE THOLEIITE
80 samples
QUARTZ THOLEIITE
144 samples
BASALT ANDESITE
31 samples
ICELANDITE
37 samples
DACITE
18 samples
RHYOLITE
108 samples
B.
38 samples
46 samples
14 samples
8 samples
3 sampl.
14 samples
0 1 2 3 4

O´Hara (1976) has shown that there is a severely restricted range of temperatures and compositions which permit a basalt to show several phenocryst species present in small amounts on eruption. Thus, in a simple three component system, a bulk composition ($<$ 10% crystalline), where 2 primocryst species are present, comprises c. 18% of the total range of compositions available. The presence of a third crystalline species would further narrow this value to only 1% of the total available range of compositions. The strongly negative correlation shown by the number of phenocryst species in the quartz normative tholeiite group (fig.11.1,A and B) with this probability calculation, where only 25-30% of the samples show the presence of 2 or more crystalline species, indicates that this restriction, which is highly applicable to basalts of MORB type, may not apply to the majority of quartz normative tholeiite basalts of Iceland. In spite of the weight of the petrographic evidence and the consistency between the research area and the other three regions (Fig.11.1,A and B), the samples would merit further verification from experimental petrology on the melting/crystallization behaviour under controlled pressure and temperature conditions.

It would appear that the varied compositions of the aphyric basalts characterizing episodes of high productivity are unlikely to have been modified by low pressure fractionation. This, however, leaves open the possibilities of primary control by depth and degree of source rock melting as well as by high pressure crystal fractionation. The likelihood of hybridisation between different magma batches at depth adds a further element of complexity.

The time variant argued above, is more adaptable to the model of partial melting as this is by definition a one stage event, whereas fractional crystallization is a two stage event. In addition, the increased compositional dispersion (extending towards more evolved basalt compositions) associated with episodes of high extrusion rate is more compatible with the partial melting model, as the increased dispersion may express, in terms of rate of magma withdrawal from the mantle, the degree of urgency of the separation of the magma from the zone of partial melting (i.e. lower degree partial melting = more evolved composition), whereas the fractionation model would predict a more primitive composition.

To sum up, there are likely to be two fundamentally different basalt types erupted in Iceland:

Of these, one type is characterized by voluminous eruptions, low rates of emission, uniformity of composition with affinity to MORB type and by the presence of two or more phenocryst species.

The other type tends to be erupted in smaller volume during episodes of high eruptive rate. It possesses much greater compositional dispersion while, at the same time, it generally lacks phenocrysts and may in some cases have been erupted at supra-liquidus temperatures.

Compositional control by low-pressure fractionation processes is suspected for the first type but would appear to be quite inapplicable for basalts of the second type.

Although this study does not allow definite conclusions to be drawn beyond that of showing that low-pressure fractionation of basalts is improbable during episodes of high extrusion rate, and that during episodes of low extrusion rate, basalt magmas may be equilibrated to low-pressure cotectic by fractionation, certain implications can be drawn from these conclusions on possible mantle conditions under which basalt magmas may be generated.

Since the Icelandic crust (8-9 km, c.f. Pálmason, 1971) is more than twice the thickness of the crust over the submarine ridge (3-4 km, c.f. fig.5-4, in Wyllie, 1971), it is apparent that, if rifting rates and mechanisms are similar in the two environments (as well as the depths of magma generation), rifting of the Icelandic crust would require more than twice the volume of magma required in the submarine ridge. Furthermore, assuming the rate of magma withdrawal from the mantle to be proportional to the rate of eruption at the surface, the former may vary widely since it has been established (chapter 9) that eruptive rates in the various sectors of the axial rift may vary by a factor of up to 5.

On the assumption that partial melting results from the adiabatic uprise of mantle material (Green and Ringwood, 1967), and that the rate of uprise is proportional to the rate of rifting, then the magma volume (X) generated by the break down of the source rock per unit time may be assumed to be roughly constant. Thus, should the magma escape from the mantle into crust (Y) be less than X, it would lead to accumulation of magma batches at the base of the crust where these would experience fractional crystallization towards relatively low-pressure (c. 2-3 kb) cotectic equilibria before entering the crust. Due to the accumulation of magma batches an increase in Y towards X = Y would be likely to occur (an increase in hydrostatic pressure, O'Hara, 1973).

If, however, a condition where $Y > X$ is assumed to prevail this would lead to the loss of any sub-crustal magma batches (disappearance of low-pressure cotectic character). With the lowering of hydrostatic pressure, which would follow, the mantle may be assumed to respond by increasing the production of magmas. This may occur by increased partial melting at shallow levels (i.e. < 15 km) where the degree of melting has previously been insufficient to permit the segregation of melt, and/or by melt segregation at lower degrees of partial melting leading to magma compositions richer in LIL.

Magmas generated at the upper levels are more likely to erupt, simply due to ease of access into the zone of rifting, thus leading to their predominance at surface. The width of the mantle zone affected may be comparable to that of the corresponding fissure-swarm. This is compatible with Sigvaldason et al. (1974) and Wood et al. (1976) who have observed that olivine tholeiite lavas are most notable outside the fissure-swarm domains. A similar conclusion may be drawn from Sæmundsson's (1976) preliminary unpublished geological map of Iceland.

The degree of partial melting is one factor critically controlling the chemical composition of the melt fraction. Evidence from experiments on garnet-lherzolite shows that, at 8% partial melting, the melt is evenly distributed along all grain boundaries (Arndt, 1977). At such low degree of melting, Arndt contends that the liquid is free to separate from residual crystals under the influence of gravity or any stress applied to the rock. From considerations on the melting behaviour in peridotites, Yoder (1976) similarily favours such melting behaviour.

The basalt compositions of the Hafnarfjall-Skarðsheiði central volcano define a continuous trend towards and into the basaltic andesite field (low-Al group). The latter part of this trend is poorly represented in other comprehensively sampled central volcanoes (e.g. Kerlingafjöll (Grönvold, 1972) Esja (Friðleifsson,

1973) and Reykjadalur (Jóhannesson, 1975), c.f. chapter 8). This trend extension may be related to the narrowness of the axial rift zone during the growth of the lenticular unit (chapter 6), thus intensifying the magma escape (and consequently allowing lower degree partial melting) from a very localized sector of the mantle. It is conceivable that the rapid extraction and eruption of magma beneath and through the central volcano would induce a relatively steep hydrostatic depression gradient, thus introducing a "suction force" leading to the separation of very small degree melt batches from the source rocks. However, the derivation of the (low-Al) basaltic andesites by partial melting and extraction under stress of Layer 4 peridotites would seem unlikely, and a more attractive alternative would be that these were produced by partial melting of the ("dry") gabbroic base of Layer 3.

Thus, should the degree of partial melting be controlled to some extent by the rate of magma escape into the crust as indicated above, it allows the following predictions to be made;

1) That within a longitudinal section of an idealized lenticular lava unit (where the extrusion rate decreases "linearly " away from the centre) a corresponding decrease in compositional dispersion may occur, coincident with the gradual thinning of the lava unit.

2) That an increased number of fissure swarms active within any crosssection of the axial rift zone may also influence the compositional dispersion within the lenticular lava units.

11.2 The origin of differentiated rocks

The early postulation, that the relative abundance of differentiated rocks in Iceland were produced by the remelting of an ancient sialic substratum, was convincingly challenged by Moorbath and Walker (1965), who showed that these rocks had $^{87}Sr/^{86}Sr$ isotopic ratios indistinguishable from the basalts, thus suggesting that they could be related to a similar source.

The hypothesis, that the differentiated rocks in Iceland were generated through fractional crystallization from a basalt parent was proposed by Carmichael (1964). He noted the apparent continuity of the chemical trends from basalt to rhyolite compositions, and also the general correspondence between chemical and petrological features. Thus he proposed that the fractionation from basalts to intermediate rocks was mainly controlled by the precipitation of Ti-magnetite as the chief-fractionating phase.

Sigurðsson (1970) came to the same conclusion from a similar orientated research in the Setberg central volcanoes in W-Iceland. In a recent paper (1977) Sigurðsson proposed that compositional variations occur within Layer 3 of the Icelandic crust, derived by fractional crystallization in magma chambers, with layered (accumulative) mafic rocks at the base, overlain by gabbros grading upwards into leucocratic differentiates near the upper limit of Layer 3 (4-5 km). These differentiates, however, are unlikely to form within the active zone of basaltic magma injection immediately under the rift, but rather some kilometers away from the axial zone. He maintains, that the majority of the rhyolites erupted in the Quaternary to Recent volcanic zones in Iceland (especially those of the eastern volcanic zone) are generated by melting of plagiogranites within Layer 3 during episodes of injection of basaltic magma into a rift zone recently established within the older crust.

Another, and more widely held hypothesis, the model of partial melting, states that the acid and intermediate rock compositions can be produced by small and more extensive degree of partial melting respectively, in the lower (gabbroic) crustal regions. This model has been favoured by Grönvold (1972), Sigvaldason (1974) and Jóhannesson (1975).

O'Nions and Grönvold (1973) showed that while the presently active central volcanoes of Námafjall (NE-Iceland) and Kerlingarfjöll (Central-Iceland) have $^{87}Sr/^{86}Sr$ ratios indistinguishable from the contemporaneous basalts, the differentiates of Torfajökull have distinctly higher $^{87}Sr/^{86}Sr$ ratios. They proposed, on the grounds of secular variation of Sr-isotope composition with time (O'Nions and Pankhurst, 1973), that the anomalously voluminous acid rocks in Torfajökull may be produced from partial melting of a 15-16 m.y. old crustal segment. They further hold that the Sr-isotopic similarities between the basalts and the differentiates in the other central volcanoes do not necessarily contradict the partial melting hypothesis due to the short time difference between the basalt accretion to the crust and its subsequent partial remelting.

The postulation of Baldridge et al. (1973) that the origin of the differentiated rocks of Hekla could be explained in terms of fractional crystallization, was challenged by Sigvaldason(1974) who maintained that Hekla produced two types of magmatic liquids; dacite and a basaltic andesite. He argued that these could have been derived by partial melting of the crust, although "some admixture of mantle material" would have been necessary to generate the basaltic andesite.

Therefore, with the exception of Baldridge et al. (1973), a general consensus appears to be that the anomalous volume of differentiated rocks extruded within the eastern volcanic zone to the south may be generated through partial melting of an older (5-16 m.y.) lithosphere.

The high thermal gradients (100-150°C km^{-1}) within the axial rift zone and central volcanoes (Pálmason, 1973) are compatible with a model of partial melting since these gradients suggest that the granite solidus could readily be attained and exceeded within Layer 3. This data is consistent with the possibility of generating differentiated rocks by crustal anatexis.

The crustal model preferred in this study (chapter 9) predicts that a number of features observed in the central volcano may causally be attributed to the anomalous growth pattern of the crust. The near exclusive confinement of differentiated rocks to the areas of central volcanic activity may further be correlated to these growth patterns.

An interesting proposal, put forward by Walker (1974) states that the crustal response to a sheet injection is largely one involving subsidence of the substrata with only a negligible surface elevation. Put into context of the crustal structure, this may imply that the thickening of Layer 3 below central volcanoes (which is likely to occur near the Layer 2/3 boundary) as a result of high intrusion rates, involves a depression of the Layer 3/4 boundary surface. The lowering of the crust into a higher temperature environment would enhance the possibility of crustal anatexis at the base of the crust. The extrusions of differentiated rocks such as at

Hvítá, Hallarmúli and Eyjafjörður (chapter 2) where tectonic evolution suggests a regional depression of the crust is fully consistent with the model of partial melting.

Jóhannesson (1975) argued against crystal fractionation in the genesis of Icelandic differentiates on the grounds that in order to produce the 15-20% differentiated rocks estimated to be present within Layers 1 and 2 of Reykjadalur central volcano, 40-70% of the underlying Layer 3 would have had to be involved in the fractionation. This, he maintained, is unlikely during such a geologically short interval within a tectonically active area. A similar argument can be proposed for the Hafnarfjall-Skarðsheiði central volcano, where it is estimated that differentiated rocks account for just over 30% of the succession (fig.11.2).

The compositions of the intermediate rocks of the Hafnarfjall-Skarðsheiði central volcano, which are most abundant adjacent to the inferred older lithospheric margin, are anomalous with respect to their iron-and Mn-enrichment (figs.8.5, 8.10 and 8.11). An almost identical chemical anomaly, noted in the Hallarmúli acid locality (Jóhannesson, 1975) about 30 km northeast of the research area, suggests that the older crust may be an influencing factor in the genesis of these magmas.

An aphyric nature is a characteristic feature of most differentiated extrusives in Iceland, a feature also evidenced in the research area. This persistent low crystal/liquid ratio of the differentiated magmas on eruption would be difficult to explain if these were generated through fractional crystallization from a basaltic parent, whereas such a feature would be expected of magmas formed by partial melting.

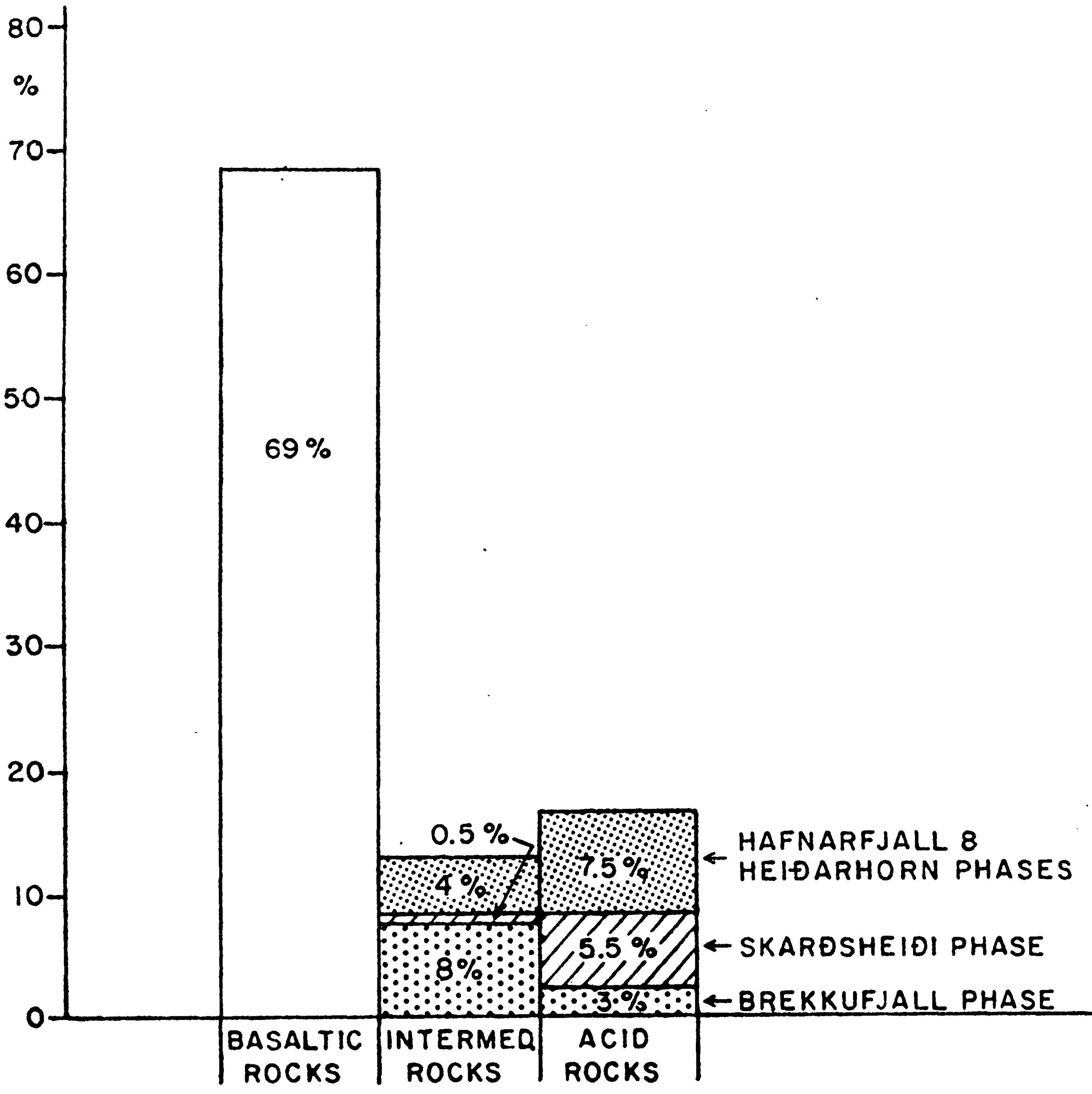


Fig. II.2

ROCK ABUNDANCIES IN THE HAFNARFJALL-SKARÐSHEIÐI LENTICULAR LAVA UNIT IN THE RESEARCH AREA (GRID COUNTING; 2000 POINTS).

The number of phenocryst phases, as shown on the histograms (fig.11.1,A and B), do not indicate any strong affinity towards two or more phase cotectic crystallization, as would be expected if its composition was controlled by fractionation. It would seem more probable that this heterogeneous (micro)phenocryst distribution reflects the initial crystallization of magma bodies (generated by partial melting) waiting for the appropriate rifting to permit it to surface.

The histograms do, however, show a notable break between the quartz tholeiites, which reflect a steady decrease in the number of (micro)phenocryst phases, and the basalt andesites (and the more acid rocks) which show a distinct heterogeneous distribution.

A bimodal distribution of rock compositions in Icelandic central volcanoes, with a maxima in the basalt and rhyolite compositions, has been pointed out (e.g. by Grönvold, 1972; Sigurðsson, 1977). A similar bimodal distribution is evident in all the volcanic phases of the Hafnarfjall-Skarðsheiði central volcano, except for the Brekku-fjall phase (fig.11.2).

The occurrences of composite rocks have been reported from several central volcanic areas (e.g. Gibson and Walker, 1964; Blake et al., 1965; Walker and Skelhorn, 1966) where their compositions, with only a few exceptions, are that of basalt and rhyolite. In addition the composite nature of many of the Icelandic rhyolitic ignimbrites has been noted by several authors (Walker, 1962; Blake, 1970; Sæmundsson, 1974; Sparks et al., 1977; c.f. chapter 3, this thesis), suggesting that the heat and volatile transfer from the hotter basic magma into the acid component played an important role in their genesis. The intrusion of basic magma into an acid magma chamber is well displayed in the large Tertiary intrusion of Austurhorn, SE-Iceland. This intrusion includes a net-veined complex characterized by rounded pillow-like masses of dolerite surrounded by granophyre (Blake et al., 1965). In order to explain the scarcity of basalt eruptives in the Torfajökull rhyolite terrain a mechanism of basalt magma trapping at the base of rhyolite magma chambers at shallow depths has been suggested (Walker, 1974).

If crustal fissuring and the concominant basalt elevation is viewed as an arbitrary interruption factor to the processes taking place in the shallow level magma chambers, the predominance of rhyolitic magma compositions in these chambers would be highly anomalous if they had evolved from a basaltic parent by a continuous fractional crystallization. The alternative process, such as favoured by O'Nions and Grönvold (1973) for the Icelandic differentiated rocks, involves the generation of rhyolites by small degree, and intermediate rocks by a larger degree partial melting in the gabbroic lower crustal regions, is more consistent with the above observations.

It has been assumed by most workers that the chemical trends from basalt to rhyolite in the Þingmúli type central volcanoes are essentially continuous (e.g. Carmichael, 1964; Sigurðsson, 1970; Grönvold, 1972). However, a relative abundance of analysed samples in the 50-56% silica interval in the Hafnarfjall-Skarðsheiði central volcano clearly indicates that the basalt-rhyolite suite consists of two trends, dislocated in the basaltic andesite range (chapter 8). A similar dislocation is likely to be present in other Icelandic central volcanoes, but have not been noted before due to the scarcity of analytical data for the (low-Al) basaltic andesite rocks. The abundance of analysed basaltic andesites (low- and high-Al groups) from other central volcanoes is summarized in table 11.5. It is interesting that most analysed basaltic andesites are of the high-Al type except for two samples from the Þingmúli and Reykjadalur central volcanoes. The table shows that, in general, the total iron and TiO_2 values also tend to fall in groupings similar to those of the Hafnarfjall-Skarðsheiði central volcano. Fig 11.4, A & B shows Al_2O_3 and the modified Larsen factor (Carmichael et al., 1974) plotted against the iron ratio. Both clearly demonstrate the clustering of data points for the low-Al group at the low-Mg termination of the basalt trend, whereas the high-Al group data points are scattered over a broader compositional field. Such scatter is also observed within the icelandite and rhyolite compositions.

The tightly restricted low-Al trend of the basaltic andesites was tentatively suggested earlier (11.1) to be more likely to have been generated by partial melting of the gabbroic base of Layer 3 rather than derived by partial melting of Layer 4 peridotites. In addition, this group tends to be scarce or absent in other Þingmúli-type central volcanoes. In contrast, the process(es) responsible for the high-Al trend of intermediate to acid magmas impose far less restrictive control on their composition.

The complex effects resulting from the introduction of water or other volatiles into crustal melting processes are still relatively unknown because of incomplete experimental evidence and uncertainities in the conditions under which such melting may occur.

Evidence on the hydrous state of the crustal Layer 3 in Iceland is circumstantial.

The progression downwards in Iceland from unzeolitized -

zeolitized - chlorite/epidote facies is analogus to that inferred from ophiolite and modern studies of the oceanic crust in general (e.g. De Wit and Stern, 1976) and carries the expectation (possibility) that at still deeper levels (unexposed in Iceland) amphibolite facies rocks may be present. An answer to such a problem may emerge from deep drilling programmes in Iceland.

It has been suggested that the variable, but generally lower ^{18}O values of the intermediate and acid rocks in Iceland indicate these magmas to be generated by hydrothermally altered crust (Muehlenbachs, 1973; Jóhannesson, 1975).

Assuming a water deficient condition (c.f. p.176, Wyllie, 1971) to prevail at least in some parts of the crustal Layer 3, the mineralogy is likely to consist largely of ol + cpx + plag or ol + cpx + plag + amph (c.f. O'Nions and Grönvold, 1973).

The introduction of amphibolite phase(s) into the mafic mineral "domain" will widen the temperature interval (generally towards lower temperature range) at which these minerals enter the melt phase. Similarily, the degree of hydration is also likely to affect the quantity of the mafic oxides entering the melt during such melting episodes. This proposition is in agreement with the much wider dispersion in the mafic oxides found in the high-Al basaltic andesites and icelandites as opposed to the more restrictive variation in the low-Al basaltic andesites, which would indicate the relative "dryness" of the latter. A relatively large dispersion in Mg and Fe has also been noted in the intermediate rocks of Kerlingarfjöll and Reykjadalur volcanoes (Grönvold, 1972; Jóhannesson, 1975).

It is interesting to note that the distinct Al-enrichment of the high-Al basaltic andesites complies with the proposal of these rocks

Central volcano	No. of samples	% Al_2O_3		% FeO^x		% TiO_2		Reference
		< 13	> 13	> 14	< 14	> 3	< 3	
Víðidalur-Vatnsdalur	0							Annels, 1968
Þingmúli	3	2	1	2	1	1	2	Carmichael, 1964
Hekla	1	0	1	0	1	0	1	Sigvaldason, 1974
Esja	1	0	1	0	1	0	1	Friðleifsson, 1973
Hallarmúli	2	0	2	1	1	0	2	Jóhannesson, 1975
Reykjadalur	13	2	11	2	11	0	13	-- " --
Laugardalur	0							-- " --
Húsafell	0							Grönvold, 1972
Námafjall	2	0	2	0	2	0	2	-- " --
Kerlingarfjöll	7	0	7	0	7	0	7	-- " --
Hafnarfjall-Skarðsheiði	13	6	7	6	7	6	7	this thesis

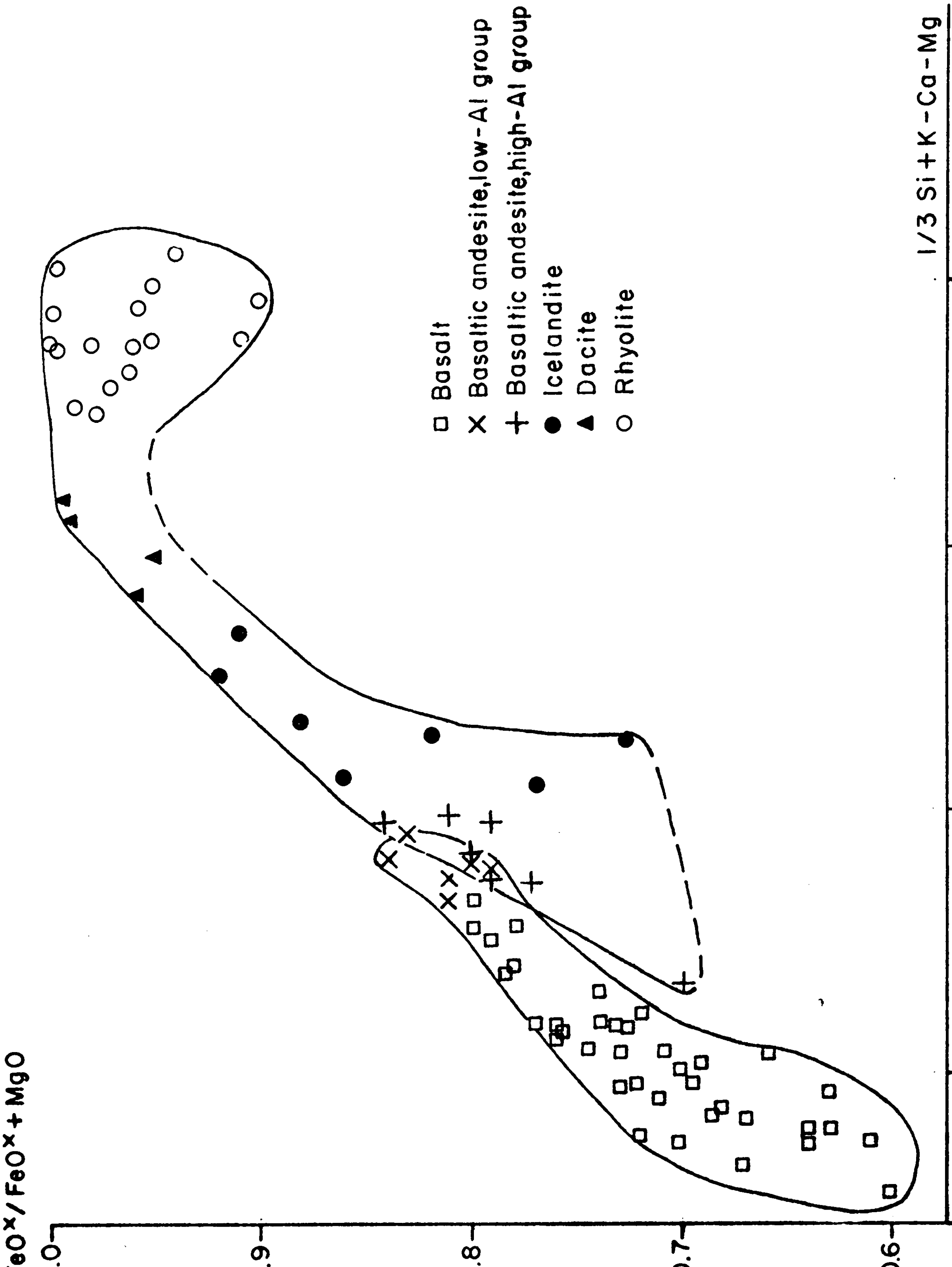
Table 11.5 The number of basaltic andesites and their division into low- and high-Al groups from eleven Þingmúli type central volcanoes.

Fig.11.4

Iron ratio of samples from Hafnarfjall-Skarðsheiði central volcano plotted against;

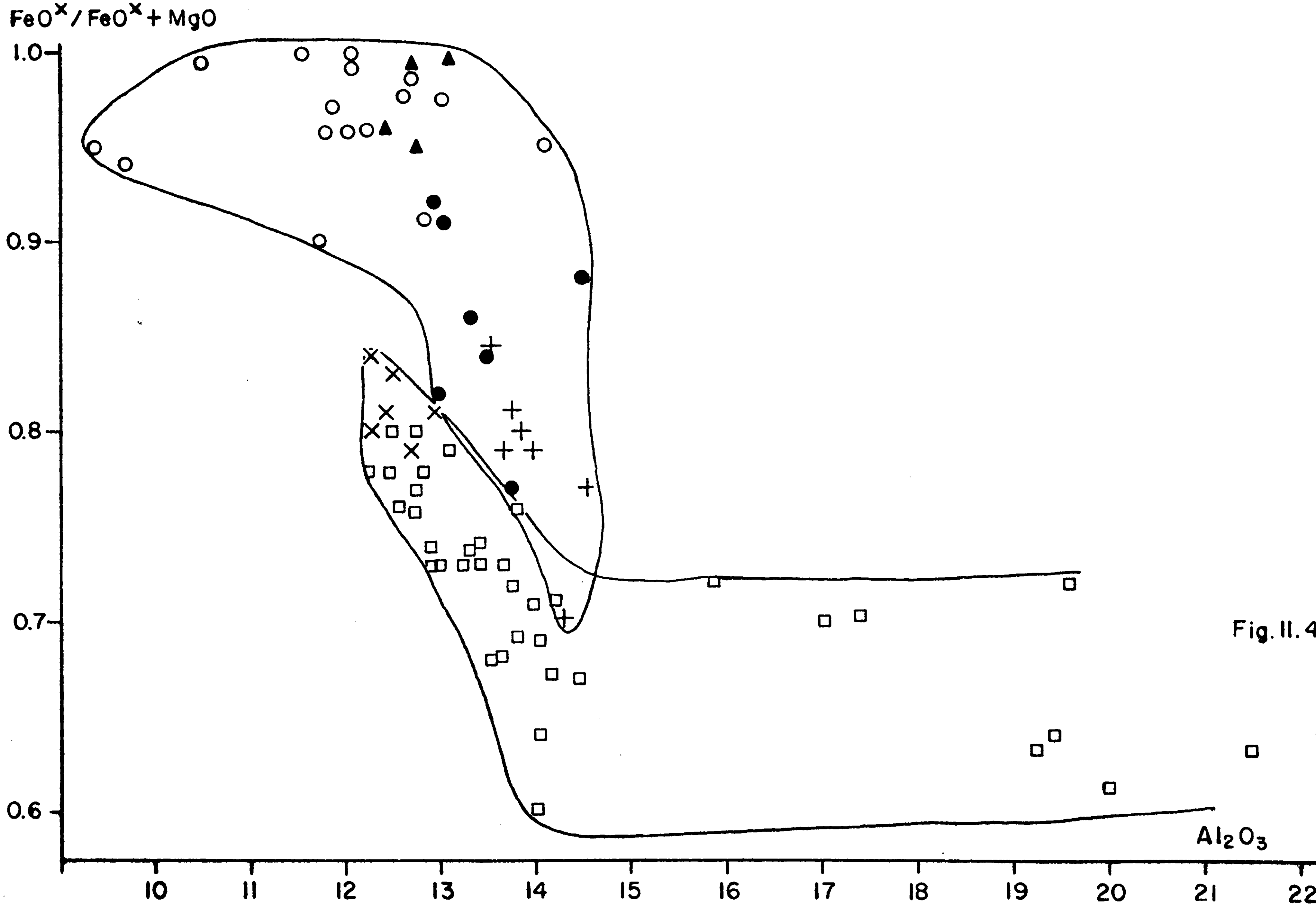
A. Modified Larsen factor.

B. Al_2O_3



FeO^x / FeO^x + MgO
1.0
0.9
0.8
0.7
0.6
-4
0
10
20
30
1/3 Si + K - Ca - Mg
□ Basalt
× Basaltic andesite, low-Al group
+ Basaltic andesite, high-Al group
● Icelandite
▲ Dacite
○ Rhyolite

Fig. II.4 A



FeO^x / FeO^x + MgO
1.0
0.9
0.8
0.7
0.6
10
11
12
13
14
15
16
17
18
19
20
21
22
Al2O3

Fig. II. 4 B

being the partial melts of amphibolites, as amphiboles of volcanic rocks, as compiled by Deer et al., 1969, generally contain 10-15% Al_2O_3, as opposed to the absence of Al in the anhydrous mafic mineral assemblage (ol + px).

In summary, the field and geochemical characteristics of the differentiated rocks in the research area are largely in agreement with the postulation that these magmas were generated by partial melting processes in the lower crustal regions. It is further postulated that the dislocation in the basaltic andesite range is caused by the introduction of a water phase into the melting processes.

APPENDIX

LOCATIONS OF STRATIGRAPHIC PROFILES.

Table A1. The number and location of stratigraphic profiles on the geological map and in the text.

Profile no.	Fig. no.	Page no.	Approximate location on geological map.
1	3.1	23	NE-Tungukollur mt.
-	3.9	43	- - -
2	3.1	23	Hafnarfjall, northeast of Flyðrur granophyre
3	-	-	Western slopes of mt. Ölver
4	3.4	29	North of Vatnshamravatn
5	-	-	C. 1 km north of Vatnshamravatn
6	-	-	East of Ferjukot farm, at Hvítá
7	3.10	46	Leirárvogur, north shore
8	-	-	North of Blautós, western Akranes
9	-	-	Akraneskaupstaður, SW-Akranes
10	3.11	49	Northern Kaldárdalur, N-Skarðsheiði
-	3.18	70	- - -
11	-	-	Northern Hornsdalur, N-Skarðsheiði
-	3.11	49	- - -
12	-	-	North of Skessuhorn, N-Skarðsheiði
13	-	-	- - - , above Brekkufjall
14	-	-	Hestfjall, northeast of Skorradalsvatn
15	3.18	70	Western Mófell, N-Skarðsheiði
16	-	-	NW - -
17	-	-	Northwest of Seldalur, NE-Skarðsheiði
18	3.25	84	West of Skessuhorn
19	-	-	Heiðarhorn, W-Skarðsheiði
-	4.1	92	- -
20	3.25	84	Southern Skarðsdalur, SW-Skarðsheiði
21	-	-	W-Akrafjall, Akranes
-	4.1	92	- -
22	3.25	84	W-Akrafjall, near Reinir farm
-	3.27	89	- - - -
23	-	-	Kjalardalur, N-Akrafjall, Akranes
-	4.1	92	- - -
24	-	-	S-Akrafjall, north of Innrihólmur farm
25	-	-	- , c. 2 km east of profile 24
26	-	-	Grafardalur, SE-Akrafjall
27	-	-	Skessuhorn, N-Skarðsheiði
28	-	-	Þverfjall, middle southern Skarðsheiði

ANALYTICAL METHODS

The rock samples were initially cut into c. 3 cm^3 chips using Cutrock hydrolic splitter. After weathered surfaces had been discarded the chips were crushed using Sturtevant jaw crusher. Following homogenization by "coning and quartering" the material was further reduced to 100-200 mesh B.S. by grinding in a tungsten carbide tema disc mill. The powdered samples were then bottled and dried for 24 hrs at 110°C.

The major element analysis were carried out in two stages:

1) Philips Automatic Spectrometer (PW1212). The method for major element analysis is similar to that developed by Rose et al. (1963) and well established in Edinburgh.

Each sample together with lanthanum oxide and lithium tetraborate (in proportions 1:1:8) was fused at 1050°C; thereafter the glass bead was crushed in a tungsten carbide barrel and the powder pressed (at 15 tons) into a disc with a backing of boric acid.

All the trace element analysis were carried out on the PW1212. The rock powder was pressed (at 15 tons) into a disc using boric acid backing. The mass absorbtion coefficients of the pressed powder discs were determined by using the single channel Philips PW1540.

The operating conditions for the PW1212 are given in table A 3. A Cr-tube was used for the major elements whereas trace elements along with Mn were determined by using a W-tube.

The data was processed using departmental computer programs (by R. C. Cheeney) which recalculates the counts using specified equations and checks for stabilized consistency and then estimates the concentrations. The programme uses the regression method for

Table A3 Operating conditions of PW1212.

Element	Peak	kV	mA	Crystal	Counter	Peak counting time	Backgr. counting time	Coll.	Vacuum
Al	K_α	60	24	PE	F	40	-	C	Y
Ba	do	80	24	LiF	S	20	20	F	N
Ca	-	40	16	PE	F	10	-	F	Y
Cu	K_α	80	24	LiF	S	40	40	F	N
Fe	do	60	24	do	F	20	-	C	Y
K	do	60	24	PE	F	10	-	C	Y
Mg	do	40	32	KAP	F	100	100	C	Y
Mn	do	60	24	LiF	F	20	20	F	Y
Ni	do	80	24	do	S	20	20	F	N
P	do	60	24	PE	F	40	40	F	Y
Rb	do	80	24	LiF	S	40	40	F	N
Si	do	60	24	PE	F	20	-	C	Y
Sr	do	80	24	LiF	S	40	40	F	N
Ti	do	60	24	do	F	20	-	C	Y
Y	do	80	24	do	S	40	40	F	N
Zn	do	80	24	do	S	40	40	F	N
Zr	do	80	24	do	S	40	40	F	N

Key: Counter: F = Flow S = Scintillation Collimator: C = Coarse F = Fine
Vacuum : Y = Yes N = No Counting time given in seconds

Table A4 Operating conditions of PW1450

Element	Peak	kV	mA	Crystal	Counter	Peak counting time	Backgr. counting time	Coll.	Vacuum
Na	K_α	50	50	TLAP	F	100	40	F	Y
Mg	K_α	50	50	TLAP	F	100	40	F	Y
Al	K_α	50	50	PE	F	40	4	C	Y
Si	K_α	50	50	PE	F	20	2	C	Y
P	K_α	50	50	GE	F	20	4	C	Y
K	K_α	50	50	LiF 200	F	10	1	F	Y
Ca	K_α	50	10		F	10	1		Y
Ti	K_α	50	50			4	1	F	Y
Mn	K_α	50	50	LiF 200	F	10	20	F	Y
Fe	K_α	50	50	LiF 200	F	10	2	F	Y

Key: Same as in Table A3.

major elements which calculates a "best fitting" regression constant or the "Davies method" for the trace elements, which performes a regression calculation on counts corrected for matrix effects.

2) Philips PW1450 sequential Automatic X-Ray Spectrometer. A total of 57 samples (40 from Heiðarhorn, 11 from Hafnarfjall-Skarðsheiði central volcano and 6 from Biskupstungur) were analysed for major elements. Furthermore, seven samples, analysed by the PW1212, were also analysed for comparison.

The sample preparations were similar to the earlier analysis except that after the fusion the molten sample was flattened into a glass disc which was then used for the analysis. The operating conditions for the PW1450 are shown in table A 4. The data was processed in a departmental program (by M. Thirlwall).

Ferrous iron was determined wet chemically for the majority of the samples using a method after Wilson (1955). However, due to the secondary oxidation suffered by most of the samples, the CIPW norms were calculated using a fixed Fe_2O_3/FeO $+Fe_2O_3$ ratio.

The sodium oxide concentrations in the samples analysed by the PW1212 were determined by wet chemistry. After the decomposition of the samples by hydrofluoric-, nitric- and sulphuric acid treatment, the sodium concentrations were determined using an EEL flame photometer, where the readings were bracketed with a series of standard solutions. A double sodium filter was used to remove calcium interference.

TABLE A4

Major element analysis of the rock samples and their CIPW norms. ($Fe_2O_3/FeO + Fe_2O_3$) fixed at 0.25)

	CV1	CV2	CV3	CV4	CV5	CV6	CV7	CV8	CV9	CV10	CV11	CV12	CV13	CV14	CV15
PERCENT															
SiO_2	51.47	48.94	47.60	48.21	49.03	50.45	50.16	48.88	49.32	51.67	48.76	49.11	47.29	49.97	49.08
Al_2O_3	13.11	13.50	12.89	12.69	13.63	12.26	12.49	12.95	14.02	12.80	17.38	12.54	14.43	13.66	13.79
FeO (Tot)	14.55	13.70	15.74	16.04	13.55	15.24	15.44	15.33	13.13	14.74	11.27	15.46	13.36	13.90	13.67
MgO	3.92	6.57	5.97	5.01	6.40	4.40	4.28	5.60	6.00	4.05	4.85	4.98	6.57	5.15	6.05
CaO	8.98	11.46	10.88	9.97	11.81	9.35	9.35	10.45	10.71	8.57	11.82	10.26	12.77	10.86	11.22
Na_2O	3.17	2.55	2.37	2.64	2.42	2.84	2.97	2.70	3.17	2.81	2.65	2.65	2.22	2.60	2.66
K_2O	0.60	0.31	0.33	0.60	0.11	0.54	0.75	0.42	0.46	0.80	0.48	0.40	0.10	0.19	0.27
TiO_2	3.61	2.53	3.51	4.10	2.59	3.88	3.79	3.14	2.64	3.83	2.25	3.70	2.73	3.05	2.72
P_2O_5	0.54	0.27	0.35	0.47	0.26	0.76	0.52	0.31	0.33	0.45	0.30	0.63	0.32	0.37	0.30
MnO	0.26	0.23	0.25	0.28	0.21	0.28	0.27	0.24	0.23	0.27	0.19	0.28	0.22	0.24	0.22
FeO (anal)	8.34	9.64	8.40	4.02	7.05	9.09	11.43	8.04	10.89	10.48	5.76	11.12	11.12	11.44	9.81
CIPW NORM															
QZ	5.41	-	0.29	1.66	0.65	5.66	3.60	0.58	-	7.07	-	3.24	-	3.58	0.16
OR	3.53	1.83	1.95	3.53	0.65	3.18	4.42	2.47	2.71	4.71	2.83	2.36	0.59	1.12	1.59
AB	26.68	21.50	20.01	22.26	20.42	23.95	25.04	22.77	26.74	23.70	22.38	22.34	18.73	21.94	22.45
AN	19.66	24.39	23.50	20.93	25.92	19.04	18.47	21.90	22.60	19.89	34.04	21.06	29.02	24.97	24.82
DI	17.70	25.14	23.26	21.07	25.38	18.57	20.39	23.05	23.28	16.36	18.61	21.28	26.36	21.86	23.72
HY	14.64	15.90	18.87	16.97	17.47	15.97	15.14	18.04	9.79	15.61	12.09	16.67	11.19	15.80	17.37
OL	-	1.79	-	-	-	-	-	-	5.23	-	1.74	-	4.24	-	-
MT	4.28	4.04	4.65	4.73	4.00	4.49	4.55	4.52	3.87	4.35	3.33	4.56	3.94	4.10	4.03
ILM	6.82	4.79	6.65	7.76	4.90	7.34	7.17	5.94	5.00	7.25	4.26	7.00	5.17	5.78	5.15
AP	1.27	0.64	0.83	1.11	0.61	1.79	1.23	0.73	0.78	1.06	0.71	1.49	0.74	0.87	0.71
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	CV16	CV17	CV18	CV19	CV20	CV21	CV22	CV23	CV24	CV25	CV26	CV27	CV28	CV29	CV30
PERCENT															
SiO_2	50.44	49.66	48.71	50.42	46.60	48.64	48.50	48.81	50.67	50.35	47.40	48.67	48.52	50.84	48.39
Al_2O_3	13.39	13.97	19.57	13.71	17.01	19.21	9.39	12.88	13.32	13.40	13.97	12.73	19.98	12.72	14.03
FeO (Tot)	13.41	13.11	14.12	13.73	13.76	9.25	9.31	15.03	14.11	14.14	12.70	15.89	8.41	15.12	12.88
MgO	5.00	5.27	5.36	5.33	5.92	5.53	5.33	5.28	4.93	4.88	8.57	4.77	5.47	3.84	7.12
CaO	10.76	12.44	13.77	10.21	12.64	13.07	13.12	10.48	9.77	10.38	12.04	10.07	13.42	8.64	12.06
Na_2O	2.82	1.99	2.24	2.62	1.98	2.32	2.32	2.87	2.80	2.77	2.23	2.78	2.35	3.34	2.37
K_2O	0.60	0.06	0.19	0.95	0.13	0.20	0.20	0.19	0.72	0.26	0.17	0.38	0.21	0.67	0.23
TiO_2	3.01	2.91	1.40	2.72	1.60	0.13	1.50	3.81	3.02	3.16	2.40	4.01	1.35	3.94	2.45
P_2O_5	0.36	0.36	0.13	0.43	0.22	0.15	0.16	0.39	0.41	0.41	0.32	0.45	0.14	0.58	0.29
MnO	0.23	0.23	0.14	0.24	0.15	19.39	0.15	0.27	0.25	0.24	0.21	0.26	0.14	0.31	0.21
FeO (anal)	8.43	5.82	4.63	7.43	5.62	9.35	10.19	11.49	9.29	9.75	9.16	11.32	4.90	10.91	7.38
CIPW NORM															
QZ	2.43	4.95	-	1.84	-	-	-	1.68	3.23	3.97	-	2.38	-	4.38	-
OR	3.53	0.35	1.06	5.58	0.77	1.18	1.18	1.12	4.24	1.53	1.00	2.24	1.24	3.95	1.35
AB	23.79	16.79	17.89	22.02	16.70	19.60	19.60	24.20	23.61	23.37	18.82	23.44	19.85	28.17	19.99
AN	22.04	28.92	40.39	22.69	37.03	41.34	41.83	21.63	21.58	23.29	27.53	21.06	43.27	17.68	26.88
DI	23.91	25.04	19.43	20.60	19.96	18.46	18.13	22.94	20.01	21.10	24.41	21.51	18.20	17.83	25.32
HY	13.80	13.71	2.45	17.09	10.21	10.20	9.96	15.87	16.45	15.61	9.92	16.05	7.08	14.72	13.63
OL	-	-	12.04	-	7.73	3.38	3.34	-	-	-	9.28	-	4.98	-	3.71
MT	3.96	3.87	3.94	4.04	4.06	2.73	2.75	4.43	4.16	4.17	3.75	4.68	2.48	4.46	3.80
ILM	5.70	5.51	2.51	5.13	3.03	2.81	2.84	7.21	5.75	5.98	4.54	7.59	2.56	7.46	4.64
AP	0.85	0.85	0.29	1.01	0.52	0.31	0.38	0.92	0.97	0.97	0.76	1.06	0.33	1.37	0.68
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	CV31	CV32	CV33	CV34	CV35	CV36	CV38	CV39	CV40	CV41	CV42	CV43	CV44	CV37	CV45
PERCENT															
SiO_2	48.33	49.04	50.58	48.47	49.07	49.70	54.19	56.42	52.49	52.99	53.17	53.02	52.80	51.41	52.45
Al_2O_3	13.79	14.16	13.23	15.86	21.44	14.18	13.73	13.73	14.30	12.31	12.71	11.32	12.29	12.48	12.41
FeO (Tot)	16.08	13.16	13.95	13.04	7.63	13.89	13.10	12.22	11.95	15.19	13.83	18.31	14.43	14.98	14.70
MgO	4.96	6.44	5.23	5.03	4.50	5.60	3.14	3.59	5.02	3.00	3.62	2.03	3.67	3.64	3.45
CaO	10.19	11.97	10.32	11.84	13.03	10.48	6.58	6.10	9.99	7.69	7.63	7.79	8.32	8.26	7.87
Na_2O	2.31	2.27	2.77	2.59	2.52	2.68	3.86	3.60	2.97	3.51	3.46	2.50	3.31	3.28	3.59
K_2O	0.13	0.14	0.32	0.18	0.34	0.27	1.25	1.48	0.61	0.92	1.07	1.04	0.60	1.06	1.05
TiO_2	3.51	2.37	2.91	2.54	1.18	2.64	2.66	1.94	2.20	3.05	3.34	2.72	3.75	3.46	3.09
P_2O_5	0.43	0.24	0.41	0.23	0.15	0.32	1.20	0.64	0.24	1.02	0.81	1.08	0.53	1.13	1.08
MnO	0.28	0.22	0.27	0.21	0.14	0.26	0.30	0.26	0.23	0.31	0.30	0.18	0.29	0.31	0.31
FeO (anal)	-	-	-	-	-	-	-	-	6.80	8.29	9.75	11.20	11.38	-	11.26
CIPW NORM															
QZ	3.53	0.78	3.56	-	-	1.71	8.99	4.08	7.32	6.93	11.81	7.77	5.34	5.31	5.47
OR	0.77	0.82	1.89	1.06	2.01	1.59	8.72	3.60	5.42	6.31	6.12	3.53	6.24	6.47	6.18
AB	19.48	19.15	23.37	21.86	21.35	22.60	30.38	25.07	29.59	29.20	21.07	27.92	27.65	28.56	30.27
AN	26.78	27.95	22.65	31.03	46.24	25.78	16.89	23.82	15.06	15.95	16.52	16.85	16.14	15.16	14.59
DI	17.36	24.46	21.35	21.61	14.32	19.86	7.66	19.91	13.84	13.86	12.90	17.48	14.58	14.70	14.57
HY	19.69	17.90	16.59	15.15	8.56	18.61	18.57	15.27	16.11	15.44	18.49	13.84	16.42	15.96	16.18
OL	-	-	-	0.09	2.75	-	-	-	-	-	-	-	-	-	-
MT	4.74	3.88	4.12	3.85	2.18	4.10	3.61	3.53	4.48	4.08	5.39	4.26	4.42	4.60	4.33
ILM	6.64	4.49	5.51	4.81	2.24	5.00	3.67	4.17	5.77	6.33	5.14	7.10	6.55	6.52	5.85
AP	1.01	0.57	0.97	0.54	0.36	0.76	1.51	0.57	2.41	1.91	2.55	1.25	2.67	2.73	2.55
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	CV46	CV47	CV48	CV49	CV50	CV51	CV52	CV53	CV54	CV55	CV56	CV57	CV58	CV59	CV60
PERCENT															
SiO_2	52.60	52.93	58.60	60.50	53.08	60.24	58.31	53.67	57.05	54.20	54.09	65.05	68.04	62.04	66.82
Al_2O_3	12.92	13.82	14.47	12.94	14.51	12.92	13.26	13.64	13.48	12.53	13.60	12.78	13.13	13.02	12.71
FeO (Tot)	14.16	13.31	12.25	9.32	12.79	12.59	12.23	13.32	12.70	14.27	13.84	9.96	7.54	10.77	8.59
MgO	3.34	3.26	1.73	2.02	3.88	1.09	1.93	3.53	2.34	2.92	2.65	0.51	0.01	1.12	0.10
CaO	7.40	7.25	5.77	7.05	7.77	5.92	6.90	8.26	5.86	4.46	7.15	3.94	3.31	5.02	3.74
Na_2O	3.72	4.01	4.23	3.66	3.38	3.47	3.75	3.37	3.91	3.72	3.56	4.43	5.01	4.18	5.04
K_2O	1.10	1.10	1.00	1.41	0.99	1.74	0.37	1.03	1.46	0.96	1.02	2.15	2.27	1.90	2.14
TiO_2	3.02	2.82	1.33	2.11	2.82	1.25	2.19	2.29	2.06	2.93	2.47	0.79	0.40	1.26	0.50
P_2O_5	1.44	1.21	0.48	0.81	0.55	0.41	0.60	0.60	0.85	0.72	1.09	0.18	0.05	0.38	0.09
MnO	0.31	0.26	0.12	0.17	0.23	0.35	0.29	0.30	0.31	0.30	0.31	0.22	0.24	0.29	0.28
FeO (anal)	8.66	7.42	6.89	5.62	6.00	4.08	8.70	10.50	6.83	10.93	8.26	3.75	5.01	7.40	6.34
CIPW NORM															
QZ	5.98	4.74	11.74	16.97	5.82	15.84	15.69	6.12	10.49	7.67	8.69	18.79	20.78	15.68	18.94
OR	6.48	6.48	5.89	8.31	5.83	10.26	2.18	6.07	8.60	5.65	6.02	12.68	13.39	11.20	12.62
AB	31.36	33.83	35.70	30.90	28.52	29.29	31.70	28.43	32.98	31.37	30.09	37.40	42.33	35.29	42.56
AN	15.25	16.41	17.50	14.68	21.43	14.50	18.23	18.99	14.87	14.61	18.09	8.62	6.62	11.13	5.73
DI	10.08	9.74	6.82	12.62	11.21	10.55	10.30	15.11	7.31	14.90	8.69	8.53	8.42	9.75	10.85
HY	17.57	16.68	15.03	7.85	16.78	12.51	12.71	15.60	16.11	14.34	17.06	9.12	5.35	10.49	5.60
OL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MT	4.17	3.93	3.62	2.75	3.77	3.72	3.61	3.93	3.75	4.21	4.09	2.94	2.23	3.18	2.54
ILM	5.71	5.34	2.52	4.00	5.34	2.37	4.15	4.34	3.90	5.55	4.69	1.50	0.76	2.39	0.95
AP	3.40	2.86	1.13	1.91	1.30	0.97	1.42	1.42	2.01	1.70	2.58	0.43	0.12	0.90	0.21
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	CV61	CV62	CV63	CV64	CV65	CV66	CV67	CV68	CV69	CV70	CV71	CV72	CV73	CV74	CV75
PERCENT															
SiO_2	65.94	63.46	72.51	74.75	76.42	78.93	74.05	73.64	75.39	74.12	80.86	75.43	80.11	76.56	75.38
Al_2O_3	15.22	12.47	12.61	14.13	12.08	10.63	12.18	11.89	11.57	12.26	9.38	12.70	9.70	11.85	12.79
FeO (Tot)	5.77	11.19	4.49	1.64	2.25	2.46	3.80	4.28	3.74	3.47	2.24	2.64	2.09	2.31	2.64
MgO	0.94	0.44	0.06	0.08	0.01	0.01	0.02	0.14	0.00	0.15	0.11	0.06	0.13	0.10	0.27
CaO	3.26	4.73	1.90	0.61	0.56	0.48	0.93	1.48	1.20	1.49	0.47	0.61	0.59	0.40	0.58
Na_2O	4.25	4.31	5.35	5.26	5.00	3.14	5.36	5.22	4.30	4.60	3.91	5.43	2.43	5.00	5.01
K_2O	3.45	2.00	2.73	3.38	3.64	4.31	3.44	2.86	3.39	3.27	2.99	3.02	4.89	3.68	3.28
TiO_2	0.89	0.89	0.18	0.11	0.03	0.02	0.09	0.20	0.11	0.19	0.00	0.10	0.01	0.04	0.07
P_2O_5	0.16	0.20	0.02	0.02	0.00	0.01	0.00	0.03	0.01	0.05	0.01	0.00	0.02	0.01	0.03
MnO	0.11	0.31	0.14	0.01	0.01	0.01	0.12	0.21	0.28	0.39	0.02	0.00	0.02	0.02	0.01
FeO (anal)	3.58	8.12	2.44	0.04	0.28	0.35	1.31	1.45	1.69	1.44	0.03	0.42	0.51	0.08	0.03
CIPW NORM															
QZ	17.76	16.99	25.62	28.92	31.48	41.68	26.54	27.83	33.20	30.11	44.61	29.71	44.93	31.81	30.54
OR	20.36	11.79	16.12	19.97	21.50	25.46	20.31	16.89	20.02	19.31	17.63	17.84	28.89	21.74	19.36
AB	35.92	36.38	45.23	44.50	41.85	26.56	43.47	44.15	36.36	38.90	31.53	45.93	20.55	40.45	42.34
AN	12.25	8.75	2.33	2.89	-	2.18	-	0.56	2.25	3.14	-	1.36	1.12	-	2.68
DI	2.45	11.77	6.18	-	2.47	0.12	4.11	5.81	3.24	3.45	1.99	1.47	1.47	1.69	-
HY	7.49	8.86	2.81	2.22	1.78	3.22	3.46	3.04	3.59	3.58	2.85	2.72	2.35	2.79	4.08
OL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MT	1.71	3.30	1.33	0.49	0.47	0.73	0.30	1.27	1.11	1.03	0.06	0.78	0.62	-	0.78
ILM	1.69	1.69	0.34	0.21	0.06	0.04	0.17	0.38	0.21	0.36	-	0.19	0.02	0.08	0.13
AP	0.38	0.47	0.05	0.05	-	0.02	-	0.07	0.02	0.12	0.02	-	0.05	0.02	0.07
COR	-	-	-	0.76	-	-	-	-	-	-	-	-	-	-	0.02
ACM	-	-	-	0.39	-	-	1.63	-	-	-	1.30	-	-	1.36	-

	CV76	CV77	CV78	CV79	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11
PERCENT															
SiO_2	76.00	71.82	75.48	54.67	48.82	48.95	48.73	48.67	49.09	48.29	48.53	49.10	49.03	48.61	48.58
Al_2O_3	11.75	13.08	12.05	13.97	15.20	15.14	17.04	15.95	15.67	15.53	15.76	14.15	15.16	17.30	14.44
FeO (Tot)	3.18	4.44	2.65	12.28	12.44	11.94	11.09	11.58	12.35	13.01	11.88	13.07	12.01	10.96	12.80
MgO	0.34	0.10	0.11	3.23	5.72	6.48	5.26	5.48	4.93	6.24	5.81	5.74	5.69	5.57	6.68
CaO	0.90	2.12	1.07	6.97	12.07	12.39	13.02	13.02	12.01	11.31	12.87	12.13	12.74	12.24	12.04
Na_2O	4.58	5.00	5.30	3.84	2.56	2.28	2.26	2.35	2.64	2.30	2.27	2.52	2.43	2.48	2.32
K_2O	3.08	2.88	3.09	1.32	0.22	0.25	0.16	0.25	0.31	0.17	0.25	0.32	0.22	0.31	0.22
TiO_2	0.10	0.37	0.17	2.42	2.53	2.18	2.07	2.31	2.59	2.67	2.28	2.55	2.33	2.16	2.50
P_2O_5	0.03	0.14	0.06	1.07	0.22	0.19	0.17	0.19	0.15	0.20	0.18	0.20	0.19	0.18	0.22
MnO	0.05	0.03	0.02	0.22	0.25	0.20	0.20	0.21	0.25	0.26	0.19	0.24	0.21	0.22	0.23
FeO (anal)	0.33	-	-	7.26	-	-	-	-	-	-	-	-	-	-	-
CIPW NORM															
QZ	33.71	26.01	30.10	8.55	-	-	0.34	-	0.32	0.22	-	0.05	0.05	-	-
OR	18.19	17.01	18.25	6.18	1.30	1.47	0.94	1.47	1.83	1.00	1.47	1.89	1.30	1.83	1.30
AB	38.72	42.28	44.75	30.30	21.60	19.24	19.08	19.83	22.28	19.41	19.16	21.26	20.51	20.93	19.57
AN	2.40	4.74	-	18.01	29.25	30.26	35.79	32.15	29.91	31.47	31.99	26.27	29.73	35.06	28.25
DI	1.62	4.30	4.33	8.61	23.93	24.47	22.70	25.57	23.63	19.10	25.12	26.78	26.42	20.00	24.53
HY	4.16	3.32	1.30	16.93	14.28	15.77	13.55	12.11	13.12	19.44	12.93	14.59	13.59	11.80	15.98
OL	-	-	-	-	0.67	0.68	-	0.62	-	-	1.09	-	-	2.63	1.35
MT	0.94	1.31	0.75	4.09	3.67	3.52	3.27	3.42	3.65	3.84	3.51	3.86	3.54	3.23	3.78
ILM	0.19	0.70	0.32	4.71	4.79	4.13	3.92	4.38	4.91	5.06	4.32	4.83	4.41	4.09	4.73
AP	0.07	0.33	0.14	2.60	0.52	0.45	0.40	0.45	0.35	0.47	0.43	0.47	0.45	0.43	0.52
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	0.06	-	-	-	-	-	-	-	-	-	-	-	-	-

	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23	H24	H25	H26
PERCENT															
SiO_2	47.95	48.19	47.76	47.19	49.11	48.69	48.44	48.05	48.58	47.08	48.60	49.10	48.67	47.89	48.20
Al_2O_3	15.49	16.09	13.62	13.54	13.28	13.53	13.71	13.51	13.98	13.10	12.52	13.16	13.52	13.27	14.10
FeO (Tot)	12.99	12.29	14.26	14.11	13.89	13.47	14.14	14.18	13.55	15.14	15.57	15.52	13.65	15.44	13.27
MgO	5.88	6.06	6.64	15.74	6.14	6.57	6.30	6.54	6.41	6.07	5.68	4.91	6.75	5.94	7.39
CaO	11.83	11.74	11.63	11.87	11.40	11.56	11.39	11.57	11.51	11.49	10.72	9.60	11.68	11.00	11.33
Na_2O	12.47	2.46	2.37	2.95	2.57	2.58	2.39	2.40	2.35	2.83	2.61	2.82	2.31	2.45	2.21
K_2O	0.26	0.28	0.35	0.24	0.26	0.46	0.24	0.31	0.28	0.47	0.32	0.44	0.23	0.16	0.34
TiO_2	2.67	2.47	2.86	2.86	2.84	2.75	2.83	2.81	2.78	3.17	3.39	3.65	2.71	3.24	2.67
P_2O_5	0.22	0.20	0.24	0.25	0.23	0.22	0.23	0.24	2.26	0.28	0.28	0.30	0.23	0.26	0.30
MnO	0.25	0.23	0.27	0.26	0.28	0.28	0.31	0.30	0.31	0.34	0.34	0.51	0.29	0.36	0.23
FeO (anal)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CIPW NORM															
QZ	-	-	-	-	0.44	-	0.04	-	0.16	-	0.82	1.99	0.04	0.19	-
OR	1.53	1.65	2.06	1.41	1.53	2.71	1.41	1.83	1.65	2.77	1.88	2.59	1.35	0.94	2.00
AB	20.84	20.76	19.99	24.33	21.68	20.92	20.17	20.25	19.82	23.88	22.00	23.78	19.48	20.66	18.64
AN	30.32	31.95	25.41	22.92	26.86	24.35	25.90	25.10	26.69	21.59	21.42	21.87	25.76	24.65	27.46
DI	22.08	20.43	25.18	28.13	25.62	25.83	23.90	25.20	23.52	27.68	24.70	19.72	25.09	23.25	21.81
HY	12.55	13.09	12.73	-	16.85	13.82	18.51	14.61	18.29	2.07	17.51	17.85	18.57	19.00	18.08
OL	3.27	3.35	4.43	12.75	-	2.66	-	2.79	-	10.89	-	-	-	-	2.34
MT	3.83	3.63	4.21	4.16	4.10	3.97	4.17	4.18	4.00	4.47	4.59	4.58	4.03	4.55	3.91
ILM	5.06	4.68	5.41	5.40	5.38	5.21	5.36	5.47	5.26	6.00	6.41	6.91	5.13	6.13	5.05
AP	0.52	0.47	0.57	0.59	0.54	0.52	0.54	0.57	0.61	0.66	0.66	0.71	0.54	0.61	0.71
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	H27	H28	H29	H30	H31	H32	H34	H35	H36	H37	H38	H40	H41	H42	S15
PERCENT															
SiO_2	48.75	47.03	48.23	48.36	47.39	47.27	48.39	48.55	48.84	48.61	48.61	47.95	48.47	48.86	48.21
Al_2O_3	14.38	17.11	13.51	14.03	14.20	14.55	14.49	15.67	14.70	13.87	13.93	13.29	13.02	13.31	14.74
FeO (Tot)	12.31	12.15	14.53	13.57	12.72	12.42	12.08	11.60	11.93	13.32	13.17	15.35	15.12	14.84	12.57
MgO	7.42	5.75	6.40	7.26	9.87	8.48	8.58	6.68	7.26	7.03	7.26	5.82	5.86	5.79	6.97
CaO	11.33	12.67	11.26	11.49	11.46	12.49	11.98	13.06	12.54	11.79	11.64	10.87	10.88	10.72	12.05
Na_2O	2.84	2.16	2.41	2.19	1.32	2.05	2.07	2.02	1.93	2.20	2.28	2.73	2.71	2.70	2.39
K_2O	0.17	0.14	0.21	0.14	0.53	0.15	0.00	0.23	0.30	0.28	0.19	0.20	0.28	0.26	0.20
TiO_2	2.32	2.51	2.88	2.53	2.10	2.18	1.82	1.83	2.07	2.41	2.44	3.11	3.04	2.90	2.41
P_2O_5	0.27	0.27	0.30	0.26	0.20	0.21	0.17	0.18	0.22	0.25	0.26	0.38	0.35	0.33	0.26
MnO	0.21	0.21	0.25	0.22	0.21	0.21	0.20	0.20	0.21	0.23	0.22	0.27	0.27	0.28	0.19
FeO (anal)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.86
CIPW NORM															
QZ	-	-	-	-	-	-	-	-	0.07	-	-	-	-	0.40	-
OR	1.00	0.83	1.24	0.82	3.12	0.88	1.18	1.36	1.77	1.65	1.12	1.18	1.65	1.53	1.18
AB	23.97	18.23	20.33	18.48	11.14	17.30	17.47	17.04	16.29	18.56	19.24	23.03	22.86	22.78	20.17
AN	25.92	36.48	25.35	27.96	31.17	29.97	29.58	32.97	30.48	27.07	27.14	23.35	22.46	23.36	28.82
DI	23.21	20.13	23.45	22.32	19.68	24.82	23.31	24.99	24.66	24.35	23.58	23.19	24.10	22.82	23.86
HY	9.83	11.54	18.87	20.46	21.17	9.35	14.82	14.32	18.77	18.38	18.40	15.90	17.24	18.47	12.74
OL	7.40	3.81	0.31	0.57	5.51	9.39	6.22	2.01	-	0.91	1.40	2.05	0.65	-	4.34
MT	3.63	3.59	4.29	3.99	3.75	3.66	3.57	3.42	3.52	3.93	3.89	4.53	4.46	4.38	3.71
ILM	4.39	4.75	5.45	4.79	3.98	4.13	3.45	3.47	3.92	4.56	4.65	4.89	5.72	5.49	4.56
AP	0.64	0.64	0.71	0.61	0.47	0.50	0.40	0.43	0.52	0.59	0.61	0.90	0.83	0.78	0.61
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	S34	S37	S41	S45	S47	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
PERCENT																
SiO_2	48.79	48.39	47.72	48.16	49.15	48.15	48.77	48.36	49.39	49.43	49.66	49.15	49.36	48.38	48.25	48.23
Al_2O_3	12.64	13.55	12.71	13.08	12.91	16.07	11.59	12.67	14.55	13.39	12.61	13.74	13.16	15.30	12.25	16.05
FeO (Tot)	14.48	14.19	15.92	15.32	14.99	10.29	16.89	15.66	12.48	14.25	15.03	13.29	14.62	11.63	16.95	10.49
MgO	6.11	6.24	5.54	5.55	5.17	9.32	4.96	5.01	6.61	5.62	5.39	6.72	16.01	7.93	5.20	9.46
CaO	11.40	11.31	10.88	10.86	10.09	12.95	9.81	9.80	12.16	10.99	10.42	12.06	10.99	12.43	9.84	12.53
Na_2O	2.56	2.62	2.55	2.63	2.74	1.88	2.59	2.94	2.41	2.57	2.69	2.33	2.51	2.02	2.36	1.87
K_2O	0.20	0.15	0.24	0.23	0.35	0.02	0.42	0.54	0.20	0.24	0.40	0.21	0.29	0.15	0.43	0.86
TiO_2	3.22	3.01	3.75	3.35	3.78	1.04	4.30	4.14	1.80	3.07	3.20	2.19	2.58	1.80	3.98	1.04
P_2O_5	0.35	0.33	0.41	0.40	0.56	0.09	0.47	0.55	0.16	0.27	0.35	0.21	0.23	0.14	0.45	0.07
MnO	0.24	0.23	0.25	0.26	0.28	0.17	0.20	0.33	0.23	0.18	0.25	0.13	0.26	0.19	0.28	0.17
FeO (anal)	8.92	8.92	6.53	11.03	11.84	8.93	13.03	-	-	9.95	12.08	11.08	-	-	-	-
CIPW NORM																
QZ	0.91	-	0.73	0.79	2.93	-	3.60	1.07	-	2.06	2.29	-	0.96	-	3.04	-
OR	1.18	0.88	1.41	1.35	2.06	0.12	2.47	3.18	1.18	1.41	2.36	1.24	1.71	0.88	2.53	0.35
AB	21.60	22.10	21.51	22.17	23.10	15.88	21.83	24.79	20.34	21.68	22.69	19.65	21.17	17.05	19.90	15.79
AN	22.34	24.69	22.45	23.12	21.81	35.28	18.69	19.71	28.22	24.21	21.08	26.33	23.71	32.16	21.48	35.15
DI	26.23	24.00	23.82	23.19	20.27	22.91	22.31	20.93	25.44	23.49	23.40	26.29	23.15	23.29	20.21	21.44
HY	16.55	16.96	17.31	17.20	16.93	10.74	16.89	16.57	15.81	16.49	16.87	17.74	18.56	14.82	19.25	12.45
OL	-	0.71	-	-	-	9.85	-	-	1.54	-	-	0.19	-	4.62	-	9.58
MT	4.27	4.18	4.70	4.52	4.42	3.04	4.96	4.62	3.68	4.20	4.43	3.92	4.31	3.43	5.00	3.10
ILM	6.10	5.70	7.10	6.72	7.15	1.97	8.14	7.83	3.41	5.81	6.06	4.15	4.88	3.41	7.53	1.97
AP	0.83	0.78	0.97	0.94	1.32	0.21	1.11	1.30	0.38	0.64	0.83	0.50	0.54	0.33	1.06	0.17
COR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ACM	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

TABLE A5

The trace element concentration of the rock samples.

PPM	CV1	CV2	CV3	CV4	CV5	CV6	CV7	CV8	CV9	CV11	CV12	CV13	CV14	CV15	CV16
Ba	224	137	276	212	109	273	264	161	315	125	489	116	213	155	201
Zr	273	150	316	223	144	304	275	184	271	158	360	121	212	171	222
Sr	248	247	272	256	241	283	279	219	244	349	304	245	342	253	280
Rb	15	9	19	12	3	17	12	7	16	11	31	6	11	13	10
Cu	30	166	24	71	149	37	77	172	38	109	12	110	152	135	105
Ni	8	47	7	29	50	12	23	35	12	32	9	69	29	48	28
Zn	129	99	128	116	84	132	131	109	136	93	134	89	67	106	110
Y	44	25	49	33	24	52	43	28	42	21	51	23	29	29	33

PPM	CV17	CV20	CV21	CV22	CV24	CV26	CV27	CV29	CV30	CV41	CV42	CV43	CV44	CV37	CV45
Ba	130	46	61	73	234	77	225	255	94	260	310	350	117	250	250
Zr	186	121	92	74	248	120	239	292	143	319	397	522	161	342	356
Sr	292	308	323	158	289	224	275	266	211	263	282	261	219	280	271
Rb	5	6	6	3	13	6	17	12	6	21	24	12	6	16	21
Cu	111	95	121	48	84	146	77	25	117	16	28	37	111	26	26
Ni	34	48	36	46	25	102	30	5	88	4	6	7	46	8	8
Zn	105	64	66	93	112	82	127	142	87	148	139	188	109	145	143
Y	23	17	12	17	35	23	35	45	23	54	55	29	70	54	58

PPM	CV46	CV47	CV48	CV49	CV51	CV52	CV53	CV54	CV55	CV56	CV57	CV58	CV59	CV60	CV61
Ba	254	258	247	283	489	-	311	315	229	300	312	-	299	388	580
Zr	359	308	284	479	619	-	444	452	337	400	1464	-	566	1162	493
Sr	277	273	189	274	304	-	262	296	260	260	175	-	243	214	206
Rb	23	23	19	25	30	-	32	25	27	19	49	-	39	54	77
Cu	11	35	35	18	15	13	61	13	20	15	27	4	12	13	32
Ni	5	15	7	6	5	5	23	6	6	4	7	6	5	6	11
Zn	145	141	137	170	160	161	140	156	140	165	158	194	154	198	74
Y	63	63	70	70	70	62	52	65	54	67	78	95	70	98	38

PPM	CV62	CV63	CV64	CV66	CV67	CV68	CV69	CV70	CV72	CV73	CV74	CV75	CV76	H3	H4
Ba	351	326	522	288	389	328	325	337	292	107	656	671	521	87	88
Zr	1545	680	657	517	567	680	515	533	542	331	550	367	504	82	80
Sr	184	106	85	18	63	78	60	78	78	21	45	68	92	329	306
Rb	50	60	70	102	70	61	63	60	63	61	74	70	65	12	11
Cu	34	3	4	29	6	6	6	4	2	11	4	7	10	-	-
Ni	5	5	6	8	9	4	6	4	4	3	5	5	7	-	-
Zn	179	150	115	121	157	105	69	127	116	56	158	134	84	93	97
Y	86	101	96	161	98	108	96	107	66	59	108	50	90	27	23

PPM	H7	H10	H17	H18	H23	H25	H32	H34	H35	H38	H40	H41	H42	S15	S34
Ba	104	103	125	149	308	144	89	74	114	140	195	209	227	97	125
Zr	88	93	131	152	279	183	84	66	66	103	180	178	170	119	172
Sr	310	331	271	249	256	245	231	206	223	199	246	242	238	273	282
Rb	9	7	12	7	9	8	2	4	9	9	8	8	10	4	1
Cu	-	-	-	-	-	-	-	-	-	-	-	-	-	99	149
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	49	44
Zn	105	96	117	142	168	140	98	98	101	116	135	133	121	90	108
Y	27	26	44	54	75	59	33	79	30	44	71	69	68	41	54

PPM	S37	S41	S45	S47	B1	B2	B5	B6	B7
Ba	137	138	138	198	27	163	126	146	109
Zr	184	213	211	253	60	211	184	199	133
Sr	257	260	269	250	152	222	225	211	166
Rb	3	3	7	8	6	12	9	11	8
Cu	142	157	258	86	116	141	149	197	136
Ni	39	38	38	27	109	21	40	35	47
Zn	109	111	116	125	70	131	110	114	100
Y	62	65	63	75	12	41	33	36	26

Table A6. SAMPLE LOCATIONS

CV1 A quartz normative tholeiite dyke cutting the Brekkufjall Caldera Series in Árdalsgil (G-2).

CV2 An olivine normative tholeiite dyke cutting the Brekkufjall Caldera Series in Árdalsgil (G-3).

CV3 A quartz normative tholeiite dyke cutting the Brekkufjall Caldera Series in Árdalsgil (G-4).

CV4 A quartz normative tholeiite dyke cutting the Brekkufjall Caldera Series in Árdalsgil (G-5).

CV5 A quartz normative tholeiite dyke cutting the Brekkufjall Caldera Series in Árdalsgil (G-6).

CV6 A quartz normative tholeiite dyke cutting the Brekkufjall Caldera Series in Árdalsgil (G-8).

CV7 A quartz normative tholeiite dyke cutting the Brekkufjall Caldera Series in Árdalsgil (G-10).

CV8 A quartz normative tholeiite dyke cutting the Brekkufjall Caldera Series (G-11).

CV9 A thick olivine normative tholeiite lava at the base of Skessuhorn.

CV10 A quartz normative tholeiite lava at the NE-caldera margin in Rauðhnúkafjall.

CV11 An olivine normative tholeiite dyke west of Klausturtunguhóll.

CV12 A quartz normative tholeiite dyke (N-S) cutting through the rhyolite lavas in Skessuhorn.

CV13 An olivine normative tholeiite from the Reinir Compound Lava Shield in Hornsdalur.

CV14 A quartz normative tholeiite dyke in the caldera in western Snókur.

CV15 A quartz normative tholeiite lava in the Hafnarfjall caldera, western Leirárdalur.

CV16 A thick quartz normative dolerite cone-sheet, western Leirárdalur, a northern extension of the Hrossatungur gabbro.

CV17 A quartz normative tholeiite sill in Leirárdalur.

CV18 An olivine normative dyke in eastern Klausturtunguhóll.

CV19 A quartz normative gabbroic cone-sheet at the northeast caldera margin in Hafnardalur.

CV20 An olivine normative gabbro in western Hafnardalur.

CV21 An olivine normative Hrossatungur gabbro, sample taken in the southern part of the intrusion.

CV22 Olivine normative Hrossatungur gabbro in the southern part of the intrusion.

CV23 A quartz normative tholeiite lava on the southern slope of Snókur.

CV24 A quartz normative tholeiite sill in Leirárdalur gully.

CV25 A quartz normative tholeiite cone-sheet in Snókur.

CV26 An olivine normative dolerite plug in Hrossatungur.

CV27 A quartz normative basalt lava in the caldera in Klausturtunguhóll.

CV28 An olivine normative Hrossatungur gabbro, in the southern part of the intrusion.

CV29 A quartz normative basalt lava in the caldera in western Leirárdalur.

CV30 A thick olivine normative tholeiite lava in northern Rauðhnúkafjall.

CV31 A quartz normative basalt lava in the caldera in Hafnardalur.

CV32 A quartz normative tholeiite dyke in Svartitindur.

CV33 A thick quartz normative tholeiite lava above the Brekkufjall Caldera Series.

CV34 An olivine normative dyke in Snókur.

CV35 An olivine normative plagioclasephyric basalt lava west of Hafnarfjall.

CV36 A quartz normative basalt breccia in Hafnarfjall caldera.

CV37 A quartz normative tholeiite plug in the caldera in Hafnardalur.

CV38 A basaltic andesite lava at the base of the Brekkufjall Flank Series.

CV39 A basaltic andesite sheet near Ferjubakki farm.

CV40 A basaltic andesite lava east of Rauðhnúkafjall.

CV41 A basaltic andesite dyke (G-7) cutting the Brekkufjall Caldera Series in Árdalsgil.

CV42 A basaltic andesite dyke (G-9) cutting the Brekkufjall Caldera Series in Árdalsgil.

CV43 A basaltic andesite cone-sheet cutting the Rauðhnúkafjall rhyolite in Tungudalur.

CV44 A basaltic andesite dyke east of Snókur.

CV45 A basaltic andesite lava in the caldera in southern Hafnardalur.

CV46 A basaltic andesite lava south of Rauðihnúkur.

CV47 A basaltic andesite lava near the base of the Brekkufjall Flank Series east of Vatnshamravatn.

CV48 An icelandite dyke in western Klausturtunguhóll.

CV49 An icelandite cone-sheet east of Hafnardalur gabbro in Hafnardalur.

CV50 A basaltic andesite from the chilled margin of Hrossatungur gabbro.

CV51 An icelandite dyke in Skálafjall.

CV52 An icelandite dyke in Snókur.

CV53 A basaltic andesite lava in eastern Rauðhnúkafjall.

CV54 An andesite lava on top of Snókur.

CV55 A basaltic andesite lava in Svartitindur.

CV56 A basaltic andesite dyke east of Klausturtunguhóll.

CV57 A dacite plug west of Hestfjall.

CV58 A dacite dyke in eastern Snókur.

CV59 An icelandite cone-sheet in western Hafnardalur.

CV60 An icelandite dyke east of Snókur.

CV61 A dacite lava in Mófell.

CV62 A dacite plug west of Hestfjall.

CV63 A rhyolitic pitchstone lobe west of Rauðihnúkur.

CV64 A rhyolite lava in western Vatnsdalur.

CV65 A rhyolite lava at the base of Drageyraröxl.

CV66 The upper rhyolite lava in Árdalsgil.

CV67 A rhyolite lava west of Seldalur.

CV68 A granophyric cone-sheet in northern Klausturtunguhóll.

CV69 The Flyðrur granophyre.

CV70 A rhyolitic plug in Skálafjall.

CV71 The upper rhyolite lava in Skessuhorn.

CV72 The Rauðihnúkur rhyolite dome.

CV73 The lower rhyolite lava in Árdalsgil.

CV74 A rhyolite lava dome in Drageyraröxl.

CV75 The lower rhyolite lava in Skessuhorn.

CV76 A rhyolite dyke in the caldera in western Leirárdalur.

CV77 A granophyric cone-sheet in northern Klausturtunguhóll.

CV78 A rhyolite lava near Ferjubakki farm.

CV79 A (dioritic) gabbro below Skessuhorn.

CV80 A olivine normative tholeiite lava lobe in Snókur.

CV81 A quartz tholeiite lava in western Hafnardalur.

CV82 A tholeiitic cone-sheet in Hafnardalur.

CV83 A basaltic andesite intrusion in western Hafnarfjall.

CV84 A basaltic andesite lava in the caldera in southern Hafnardalur.

CV85 The Drageyraröxl ignimbrite feeder.

H1-H42	40 basalt samples taken from a profile in Heiðarhorn (c.f.8.13). The sample numbers refer to their stratigraphic position within the sequence.
S15,S34,S37 S41,S45,S47	6 basalt samples taken in Skarðshyrna, about 2 km south of Heiðarhorn. The sample numbers refer to the approximate stratigraphic position relative to the Heiðarhorn profile (H1-H42).
B2-B10	Fell Formation. 9 basalt lavas taken from a sequence (totalling c. 12 lavas) in Fellsfjall and Gýgjarhólsfjall in Biskupstungur.
B1	An olivine tholeiite compound lava forming the top of the sequence in Gullfoss gorge.
B11	The Lyngdalsheiði compound lava shield. Sample taken at Brúará.

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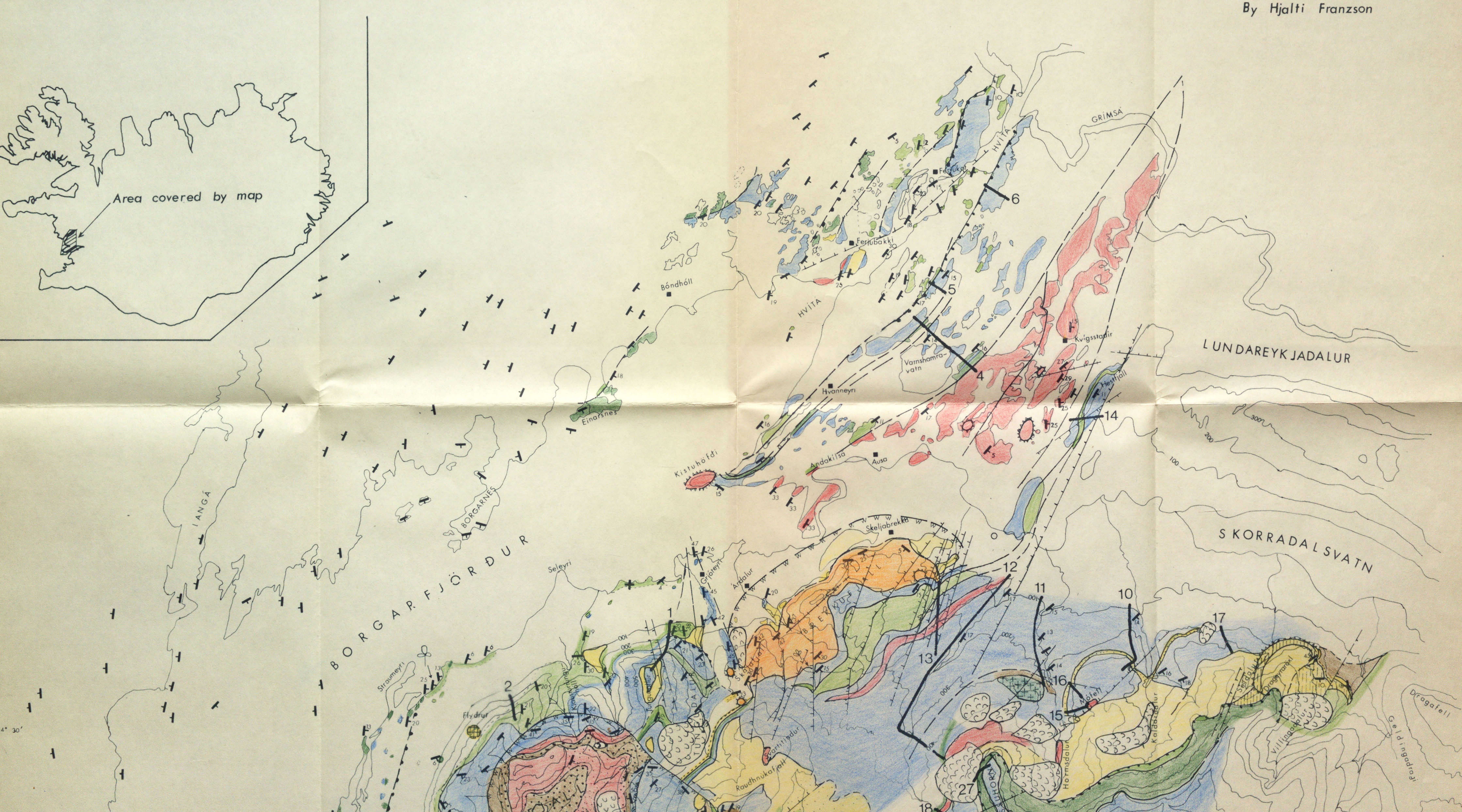
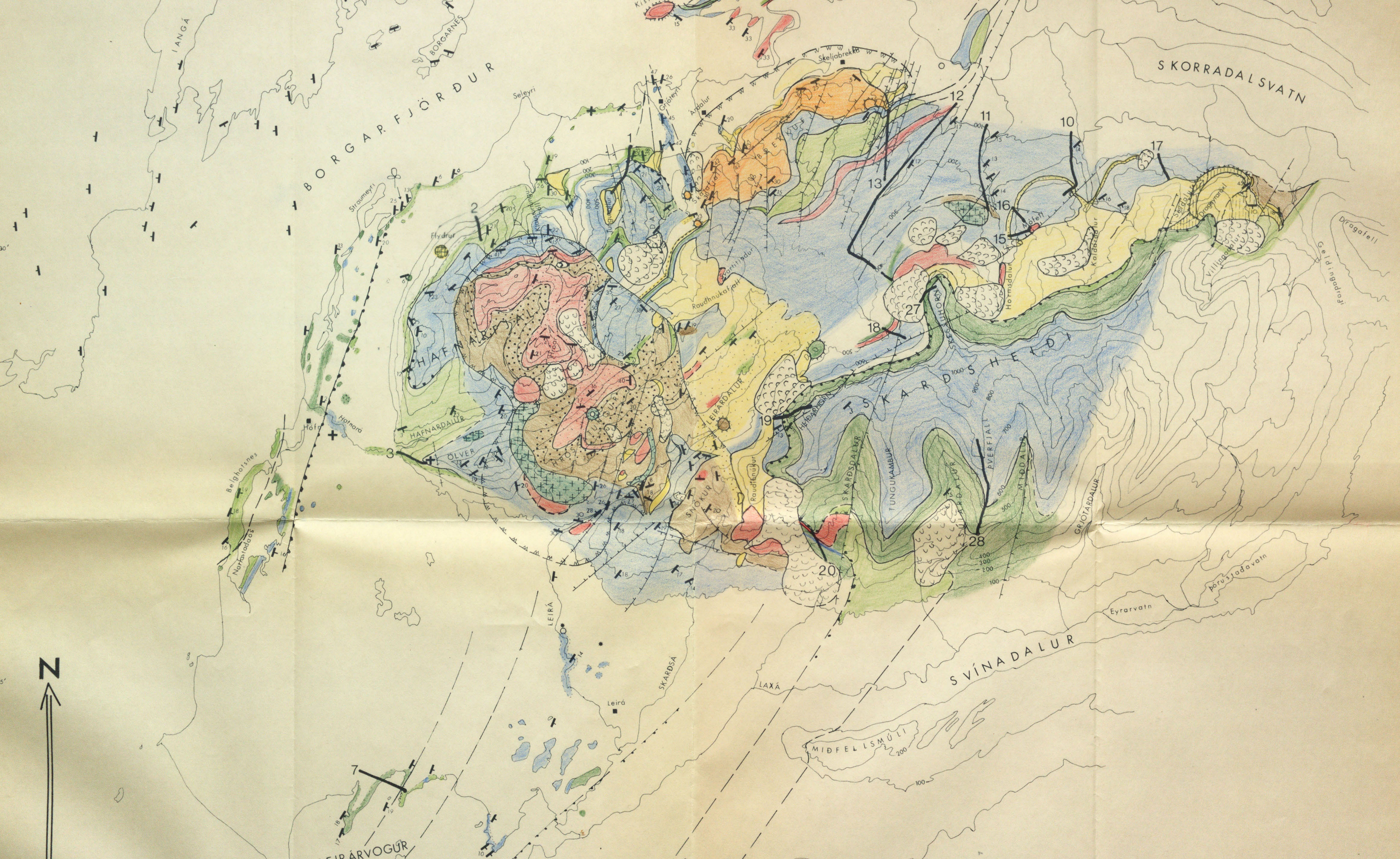
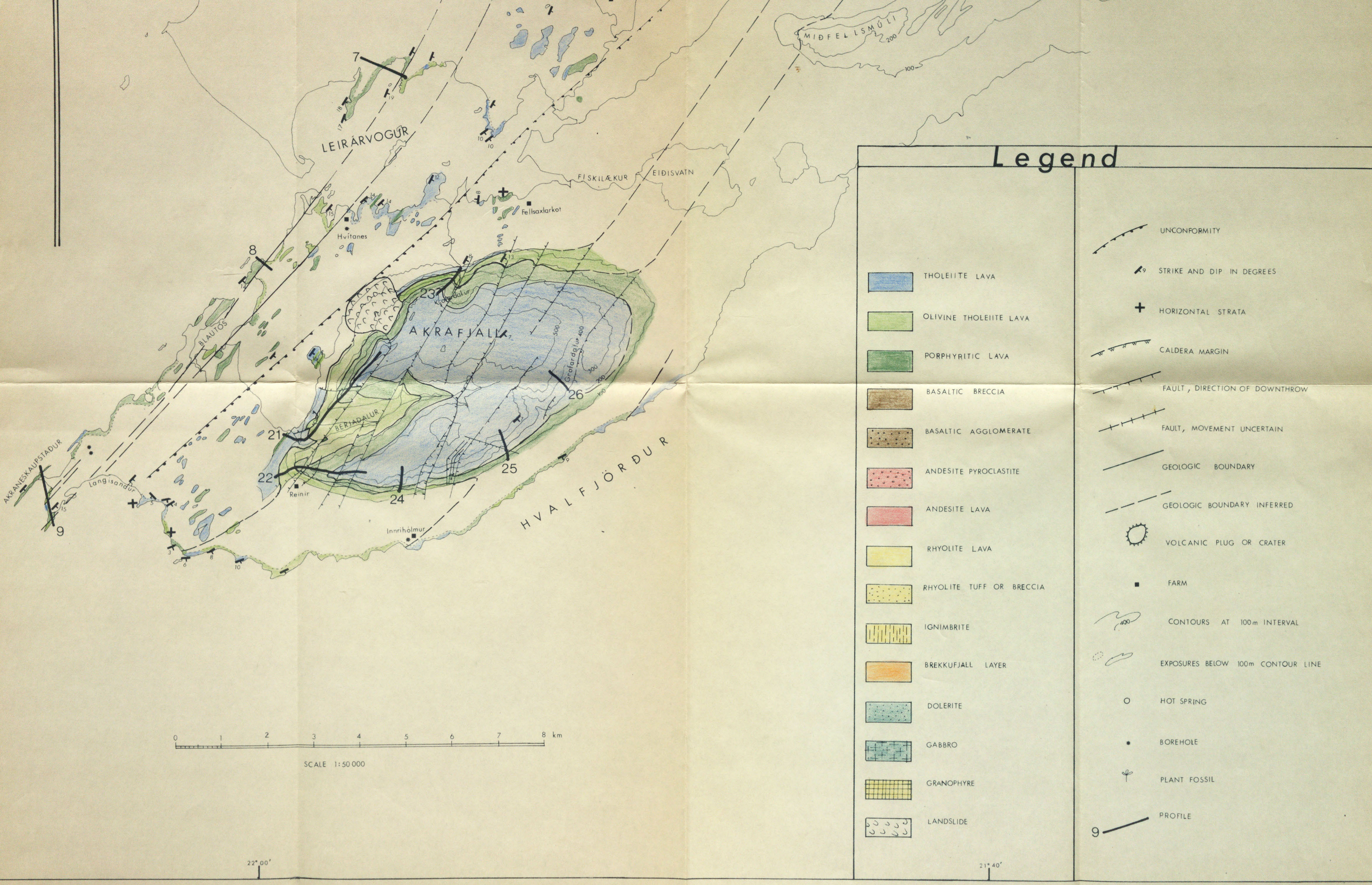
GEOLOGICAL MAP OF THE HAFNARFJALL – SKARÐSHEIÐI CENTRAL VOLCANO

By Hjalti Franzson





BORGARFJÖRÐUR
BORGARNES
Seleyri
Skeljabrekka
SKORRADALSVATN
Hafnarfjall
Hafnardalur
Ölver
Leirárdalur
SKARÐSHEIÐI
Skarðsdalur
Tungukambur
Þverfjall
Miðdalur
Grjótárdalur
Dragafell
Geldingadragi
Villingadalur
Hornsdalur
Leirá
Skarðsá
Laxá
Eyrarvatn
Þórisstaðavatn
SVÍNADALUR
MIÐFELLSMÚLI
N



Legend
THOLEIITE LAVA
OLIVINE THOLEIITE LAVA
PORPHYRITIC LAVA
BASALTIC BRECCIA
BASALTIC AGGLOMERATE
ANDESITE PYROCLASTITE
ANDESITE LAVA
RHYOLITE LAVA
RHYOLITE TUFF OR BRECCIA
IGNIMBRITE
BREKKUFJALL LAYER
DOLERITE
GABBRO
GRANOPHYRE
LANDSLIDE
UNCONFORMITY
STRIKE AND DIP IN DEGREES
HORIZONTAL STRATA
CALDERA MARGIN
FAULT, DIRECTION OF DOWNTHROW
FAULT, MOVEMENT UNCERTAIN
GEOLOGIC BOUNDARY
GEOLOGIC BOUNDARY INFERRED
VOLCANIC PLUG OR CRATER
FARM
CONTOURS AT 100m INTERVAL
EXPOSURES BELOW 100m CONTOUR LINE
HOT SPRING
BOREHOLE
PLANT FOSSIL
PROFILE
LEIRÁRVOGUR
MIÐFELLSMÚLI
FISKILÆKUR
EIÐISVATN
Fellsaxlarkot
Hvítanes
BLAUTÓS
AKRAFJALL
BERJADALUR
Grafardalur
AKRANESKAUPSTAÐUR
Langisandur
Reinir
Innrihólmur
HVALFJÖRÐUR
SCALE 1:50 000
0 1 2 3 4 5 6 7 8 km
22°00'
21°40'